MODIFIED COMPARATIVE LIFE CYCLE ASSESSMENT OF END-OF-LIFE OPTIONS FOR POST-CONSUMER PRODUCTS IN URBAN REGIONS

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Caroline Guidry

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MODIFIED COMPARATIVE LIFE CYCLE ASSESSMENT

OF END-OF-LIFE OPTIONS FOR

POST-CONSUMER PRODUCTIN IN URBAN REGIONS

Approved by:

Dr. Bert Bras, Advisor
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Chris Paredis
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Matthew Realff
School of Chemical Engineering
Georgia Institute of Technology

Date Approved: July 7th, 2008

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NOMENCLATURE

BLS	Bureau of Labor Statistics
CAP	Criteria Air Pollutants
EOL	End of Life
EPA	Environmental Protection Agency
FE	Fuel Economy
GHG	Greenhouse Gases
GWP	Global Warming Potential
HDDV	Heavy Duty Diesel Vehicle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
microDALY	micro Disability-Adjusted Life-Years
PCC	Post-consumer Carpet
PIE	Product Inventory Estimate
PMR	Primary Material Reclamation
RMR	Repurpose Material Reclamation
SMR	Secondary Material Reclamation
TBL	Triple Bottom Line
WD	Waste Disposal

SUMMARY

The environmental impact of consumer goods is becoming a growing concern in the modern world. With the increasing awareness of our daily impact and our effects on such crises as global warming, there has been a recent push to develop improved environmental strategies and new industries focused on sustainability and the recycling of a variety of post-consumer goods. In other words, there is a shift towards turning waste into money in the name of the environment. Urban regions provide the perfect setting for such development. The concentration of post-consumer waste makes the mining of recyclable materials economical and the availability of labor needed to support the emerging sustainable industries sets the stage for social, economic and environmental benefits.

There are currently several end-of-life (EOL) options for post-consumer products. EOL scenarios include material reclamation, secondary material reclamation, repurpose material reclamation, and waste disposal. Within each of these EOL scenarios exists a myriad of process permutations ranging from various collection schemes and modes of transportation to material processing standards and new recycled-content product industries. Due to the variety of EOL options for post-consumer products, there is no straight-forward answer to the question – Which EOL option is preferred? Thus, under the guidelines of Life Cycle Assessment as standardized by the International Organization of Standardization in the ISO14040: Environmental Management series, with the inclusion of social and economic indicators as well, the various EOL scenarios are compared in several impact categories including energy use, greenhouse gas emissions, criteria pollutants, solid waste generation, social implications and economic

viability. The results of this comparative analysis provide insight into the potential of a more sustainable urban environment, which is part of a much larger goal of reducing our daily impact on the world around us.

One industry sector that contributes to a significant amount of post-consumer trash each year, nearly 4.7 billion tons, is the carpet industry. According to the Environmental Protection Agency Carpet occupies a great percentage of overall dedicated landfill waste space, nationally 1% by weight and 2% by volume. Within an urban environment, the burden of such a bulky waste product is more evident; thus carpet is used here as a case study for the social, economic and environmental impacts of material mining in urban regions for the improvement of overall industrial sustainability. A comparative EOL study is conducted to assess the social, economic and environmental effects of material reclamation, secondary material reclamation, repurpose material reclamation, and waste disposal strategies of post-consumer carpet within the thirteen county urban region of Atlanta, Georgia. The EOL options discussed cover Nylon 6, Nylon 6,6, and Polyvinylchloride carpet materials in addition to an array of carpet and recycling mechanical and chemical processes. In addition the processing, each scenario will include the impacts of a variety of material collection schemes used to represent various PCC collection strategies that could be implemented to spark the carpet recycling efforts. From these assessments waste management strategies will be recommended based on the comparative impacts. Some sensitivity of these recommendations based on data and process changes will be conducted in order to determine the recommendation tipping point for each comparative assessment. Additionally, each unit process and material will be isolated within each assessment in order to highlight the hurdles or encouraging statistics with regards to PCC waste management strategies in the Atlanta metropolitan region.

CHAPTER 1
INTROCUTION AND MOTIVATION: MATERIAL MINING IN URBAN REGIONS

1.1 Picture of Urban Industrial Life Today

Humans have always significantly impacted the earth and the environment around us. However, since the industrial revolution, humanity's impact has taken a severe turn for the worse. The changes inflicted by man on the environment have skewed the delicate balance of the ecosystem and magnified such phenomenon as global warming, holes in the ozone layer and acid rain. Thus, the same industrialized engineering feats that led to our current comfortable standards of living have also been the main contributors to the environment's demise. This contradiction between comfortable living today and the downfall of the earth has created an abrasive dynamic between the political, scientific and industrial world. The tension between maintaining a desired standard of living today and ensuring the same or better standards for future generations has lead to many investigations and debates regarding the current levels of sustainability with respect to our industrialized practices and current standards of living.

In 1992, around 200 nations gathered in Rio de Janeiro, Brazil at the world's first "Earth Summit" to discuss the increasing concerns of our negative impacts on the environment. At the Summit, 154 nations signed the United Nations Framework Convention on Climate Change (UNFCCC) as an agreement to investigate and address the issues concerning global climate change (EPA, 2006). This convention marked the beginning of large-scale studies regarding current sustainability, policy changes implemented by a variety of countries and a commitment from much of the scientific community to research, develop and improve the industrial practices of today so that we may halt and perhaps reverse the damage that we have caused the earth over the last two centuries (EPA, 2006).

The US, one year after signing the UNFCCC in 1992, created the Climate Change Action Plan (CCAP), which sought voluntary cooperation of the national, state and local governments, industries and private citizens to encourage the development and deployment of cost-effective means of reducing domestic greenhouse gas (GHG) emissions. Out of CCAP sprung several Environmental Protection Agency (EPA) projects including (i) the Landfill Methane Outreach Program of 1994, which sought to reduce methane (CH_4) emissions from landfills by capturing the gas to produce energy, (ii) the Climate and Waste Program, which encouraged general reuse, recycling and source reduction policies, (iii) the Green Power Partnership, which aided in the development and deployment of renewable energy, and (iv) amendments to the Clean Air Act (CAA)which focuses on cleaning up the pollution resulting from transportation and vehicles use (EPA, 2006).

Even after all of the policy changes and voluntary programs sponsored and supported by our national, state and local governments, the US is still the largest contributor to global GHG emissions, and currently this percentage is still growing. Since 1990, the US has seen an increase of carbon dioxide (CO_2) emissions of 20%, and this number will rise another 15% by 2020 if nothing is done to change the industrial and consumer practices of our country. This prediction is a little terrifying considering the fact that the US need to reduce GHG emissions by 80% before the year 2050 in order to prevent the worst predicted consequences of global warming (EDF, 2007). In addition to the GHGs and air pollutions, Americans produce roughly 4.5lbs of solid waste per person per day. This amounts to 251million annual pounds of municipal solid waste (MSW) (EPA, 2007). Thus it would behoove the US to take a more aggressive approach towards waste management, pollution and environmental protection in general.

1.2 Material Mining in Urban Regions

Not only are US industrial practices themselves inefficient and consequently unsustainable in general, our current standards of living do not help the situation either (Gore and Blood, 2006). The consumer culture is particularly wasteful and excessive. The commercialized world in which we live bombards us with the latest and greatest gadgets and consequently has bred consumers who are constantly looking to upgrade and throw away "old" goods before the end of their useful life. This leads to quite an appalling amount of municipal solid waste (MSW) each year, the impact of which is becoming increasingly great as the population rises. As the number of people increases, waste grows while free land space, and landfill land space declines. The following figures display the US MSW generation trends per capita and in annual totals spanning between 1960 and 2005 and the landfill availability trends from 1988 to 2006.

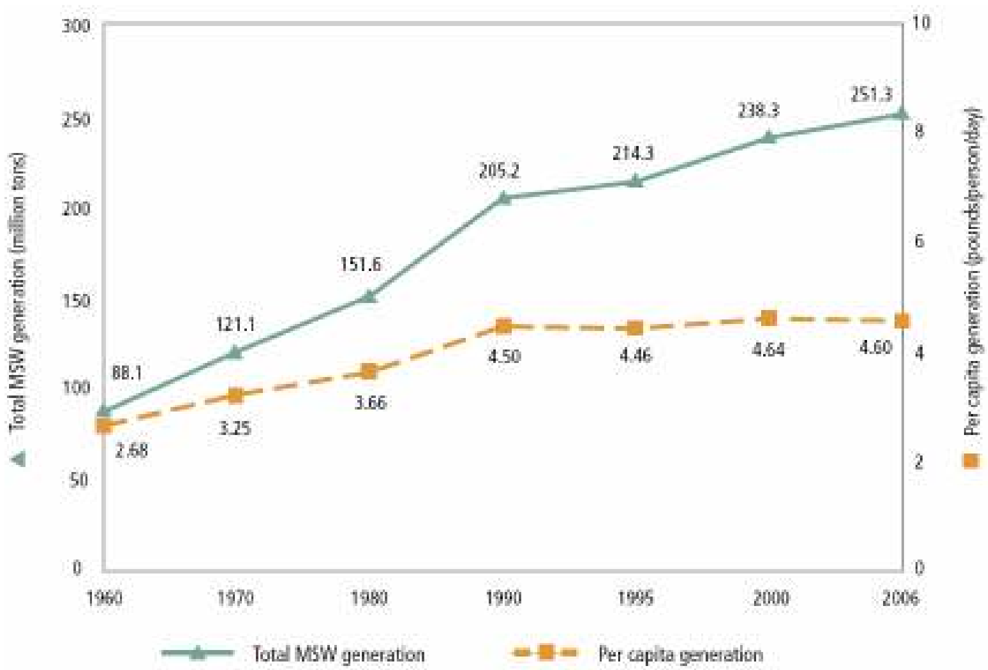


Figure 1.1: MSW Generation Rates from 1960 – 2006 (EPA, 2007)

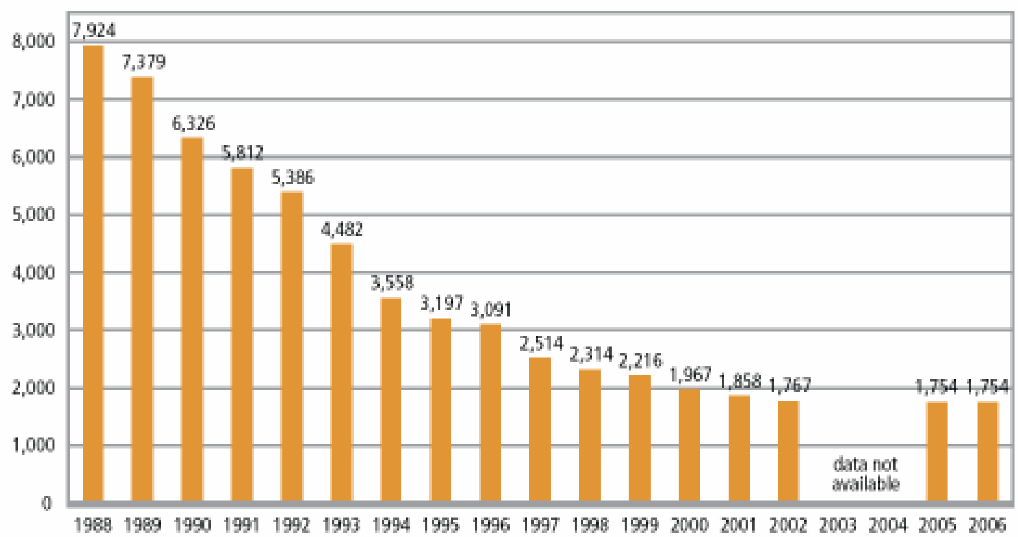


Figure 1.2: Number of Landfills in the United States by Year, 1988-2006 (EPA, 2007)

This paradox between increased generation in waste and the declining availability of landfills is most noticeable in urban regions, which are densely populated and thus have higher concentrations of people and their post-consumer waste. Thus, urban regions become a prime spot for exploring the potential positive impacts of more sustainable

MSW management and post-consumer product end-of-life (EOL) practices. The idea is that the materials thrown away could be "mined," much like virgin materials are mined, for use in new recycled-content products. The idea that today's trash is tomorrow's treasure is a real possibility and a step closer to a new and more sustainable overall industrial system.

Not only is there a potential for environmental improvements with mining post-consumer materials in urban regions, but there exists the possibility for social and economic benefits as well. A common problem in densely populated urban regions is unemployment of laborers. In 2007, the national annual average unemployment rate was 4.6%; this translates to a little over seven million unemployed laborers (BLS, 2007). Thus, the introduction of recycling industries and the infrastructure needed to support them would provide opportunities for employing the unemployed. This would then lead to an increase in local economic development. Additionally, urban regions incur great costs in disposing of waste in landfills. When landfill space is scarce, and the demand for such space is great, the supply cannot adequately meet the demands and thus the costs begin soar. Tipping fees themselves can become quite steep. The national average tipping fee for 2004 was $34.29 per ton. However, the tipping fees of the more densely populated northeastern region of the US were as high as $70.53 per ton (Repa, 2005). Thus, if the local fees themselves become to much to bear, waste is shipped out of the region at a national export average of 9.4%, which represents a loss of local economic activity as people begin to pay for the transportation of trash out of the region and for non-local tipping fees (Repa, 2005). This transplanting of waste does not solve any problems, but instead literally dumps the problem on another community's shoulders for a small fee. Thus, mining materials from urban regions in order to support new recycling industries has the potential to spawn environmental, social and economic benefits that are not realized with current MSW management strategies or consumer product EOL scenarios.

1.3 End-of-Life Activities

There are actually several EOL options for consumer goods. The most typical, which is considered the baseline for sustainable comparisons, is disposal in a landfill. However, landfilling is not the only EOL activity. Table 1.1 contains a brief description of the generic EOL options available for post-consumer products.

Table 1.1: Generic End-of-Life Options

EOL Options:	Category:	Description:
Waste Disposal	landfill	dumping of discarded goods in landfill
	landfill w/ energy capture	capturing gas, such as methane, from anaerobic activities in landfill decomposition for conversion into electric energy
	waste-to-energy	incineration of trash at facility designed to capture heat and convert to electric energy
	incineration	burning of trash without energy capture
	compost	disposal of bio-materials for anaerobic decomposition
Reuse	repurpose	extended product life through second use phase, no mechanical or chemical processing of product before second use phase
	remanufacture	repair or revamping of products for deployment in second use phase defined in same context as first use
Recycle	open-loop	mechanical and/or chemical processing of a product and/or product materials back into their original form
	closed-loop	mechanical and/or chemical processing of a product and/or product materials into a new form
	up-cycle	mechanical and/or chemical processing of materials into new materials of a greater value
	down-cycle	mechanical and/or chemical processing of materials into new materials of a lesser value

1.4 Impacts of Consumer Goods over a Life Cycle

A product life cycle begins with the acquisition of material inputs (virgin or recycled), the manufacturing phase, the use phase, and the EOL phase. Environmental, social and economic impacts exist during each of these phases of a product life cycle. The following diagram is a depiction of the sources and sinks of GHG emissions over a product's life cycle.

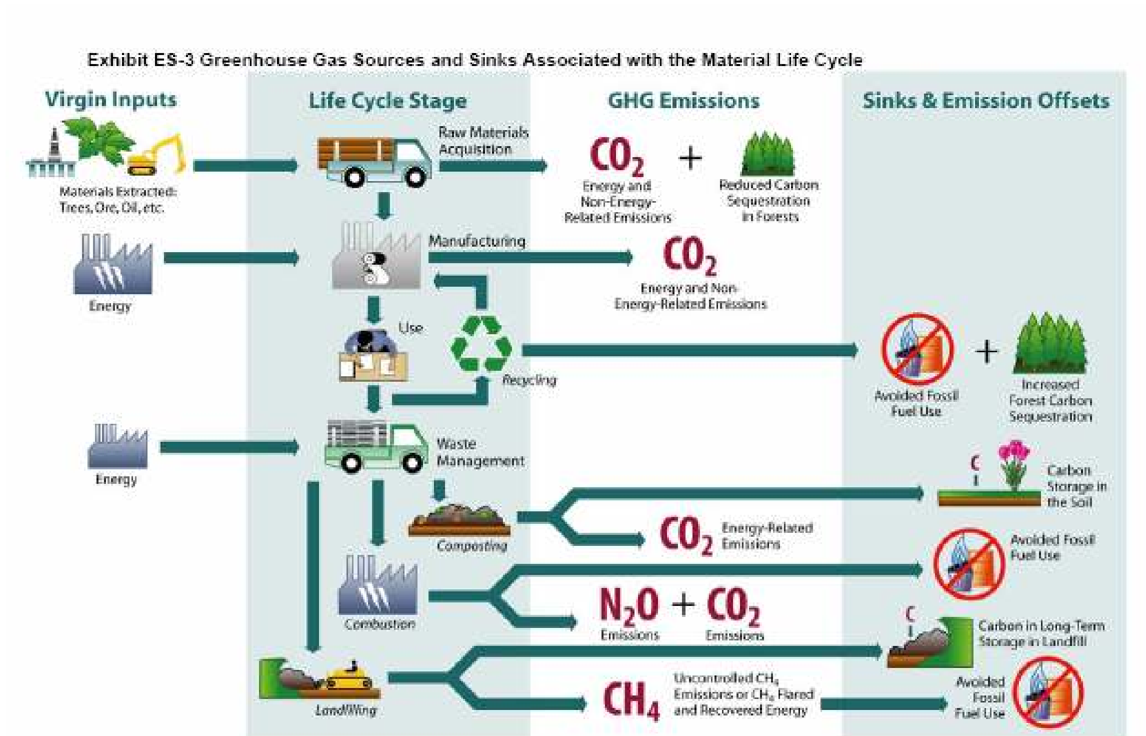


Figure 1.3: GHG Sources and Sinks Associated with the Material Life Cycle (EPA, 2006)

The ultimate goal of assessing a product's impact is to maximize the positive impacts while minimizing the negative impacts over its entire life. Traditionally, industry practices focused solely on the bottom line or the economic impacts of the first two phases of a product's life, virgin inputs and manufacturing. Industries generally seek to minimize costs and maximize profits with little regard for the use phase and EOL phase of the product. However, a new bottom line is slowly emerging that takes a more sustainable approach to a product's life. This bottom line, a triple bottom line (TBL), takes into account the environmental, social and economic impacts of a product over its entire life. By focusing on this TBL perspective over a product's complete life cycle, the more global issues of sustainability can be realized and hopefully maximized.

The specific impact categories considered in a TBL assessment vary depending on the perspective of the party conducting the study, the mandated and voluntary responsibilities of all parties involved and the perceived importance of each impact category by the responsible parties. Traditionally, environmental impacts include the assessment of solid wastes, pollutant emissions into the air, soil and water and land use. The social impacts vary from consumer safety to public health to employment and labor conditions. Lastly, the economic impacts considered are generally capitol investments, operating costs, and profits.

1.5 Post-Consumer Carpet as a Commodity

One industry sector that contributes to a rather large amount of post-consumer trash each year, nearly 4.7 billion metric tons, is the carpet industry. Carpet occupies a great percentage of overall dedicated waste space. Nationally, post-consumer carpet (PCC) contributes to 1% of the total MSW stream by weight and 2% by volume. Considering all the post-consumer products that are included in the MSW stream, the 1% by weight and 2% by volume occupied by PCC is quite a significant amount. Thus, there would appear to be inherent benefits in exploring various EOL options and eventually diverging from the current baseline PCC EOL scenario, landfilling (EPA, 2006).

Not only has the EPA taken note of the effects of PCC on the national MSW stream, but the carpet industry itself has decided to take matters into its own hands. In

2002, the Memorandum of Understanding for Carpet Stewardship (MOU) was signed by representatives from the carpet industry, government agencies and non-government organizations. The goal of the MOU is to achieve 40% PCC landfill diversion by 2012. Out of the MOU a non-profit organization, Carpet America Recovery Effort (C.A.R.E.), was formed as a third-party evaluator and entrepreneurial fostering body dedicated to helping the carpet industry meet the demands outlined in the MOU. This has led to serious initiatives by many carpet manufacturers, carpet chemical producers and entrepreneurs to develop PCC collection strategies, PCC-recycled content products, "closed-loop" recycled carpets and more sustainable flooring alternatives (CARE, 2006).

Carpet makes a great case study for product life cycle assessments. Over 50% of the materials are petroleum based which are increasing in price as the reserves are being depleted. The cost of the virgin materials is also environmental as concerns about global warming and environmental suitability grow. PCC occupies a relatively large percentage of the MSW stream and landfill space. It is used in both residential homes and commercial or business offices; therefore it is a representative commodity of all building sectors. Additionally, carpet is used by many people and is thus a good representation of a commodity used by every economic sector. Lastly, there is quite an entrepreneurial spirit and committed dedication, in part due to C.A.R.E and the MOU, to cleaning up this portion of the national waste stream. This has led to emerging technologies and products dedicated to PCC EOL uses.

Carpet EOL management options, although based on the generalized management options discussed in Section 1.3, are slightly more refined and have a different nomenclature, which will be used throughout this study. The definitions of the generic EOL options for PCC are discussed below.

Waste disposal (WD) includes four distinct EOL scenarios. The first waste disposal scenario is defined by the collection and dumping of post-consumer products in a landfill. In the second WD EOL scenario, the post-consumer products are collected and then incinerated. The final waste disposal scenario is defined by the collection and burning of post-consumer products for the purpose of converting waste-to-energy (WTE) in a cement kiln or other WTE facilities (Realff, 2007). Additionally, biodegradable organic wastes can be composted where an anaerobic decomposition of the materials occurs (EPA, 2006).

Repurpose material reclamation (RMR) implies that post-consumer products are collected and reused for the same purpose or for a different purpose as is. The distinct characteristic of the repurpose material reclamation EOL scenario is that the post-consumer product is used without any material or chemical processing. The post-consumer product may be cleaned, but actual chemical or mechanical processing does not occur prior to reuse (Realff, 2007).

In the **primary material reclamation (PMR)** EOL category, post-consumer products are collected and the materials are processed back into their original form. This scenario is the most classically sustainable in that a product at the end of its primary use is recycled back into itself. PMR is also referred to as "close-loop" recycling (Realff, 2007).

Secondary material reclamation (SMR) is defined by the reclamation of post-consumer products for the purpose of processing the reclaimed product for use in a new or different product. This is known as “open-loop” recycling. In other words, the post-consumer product is processed and used as an input into something other than the original product (Realff, 2007).

1.6 Atlanta as a Representative Metropolitan Region

Material mining in urban regions, the coined concept of using the waste generated in densely populated regions as inputs into the industrial sector for the manufacturing of new goods, is one of the key components of this study. The thirteen county Atlanta Metropolitan Region is used here as the urban region model used to assess the life cycle of PCC. The Atlanta Metropolitan Region is a representative region of a rapidly developing urban area with a growing concern for the rising demands in environmental awareness and policy. Traditionally, the southern region has some of the lowest tipping fees and thus is an accumulator of waste from all parts of the country. Georgia imports over one million metric tons of MSW annually. Thus, assuming 1% of the MSW is carpet (as estimated by the EPA), that translates to nearly 10,000 metric tons of PCC carpet imported in addition to 1% of 10.7 million metric tons of MSW generated locally. This leads to roughly 127,000 metric tons of PCC in Georgia each year (EPA, 2006; Repa, 2005).

Atlanta, in the special case of carpet, is also unique in that Dalton, Georgia, which is only an hour and a half away (approximately 90 miles), is the “Carpet Capitol of the World.”

Figure 1.4: Carpet Manufacturing Plants in the US (CRI, 2007)

Out of 240 total carpet manufacturing plants in the US, 174 are located in Georgia. Eighty percent of all US carpet is manufactured within a sixty-five mile radius of Dalton, and eight out of the thirteen, including the top four, carpet companies are headquartered in Georgia (CRI, 2007).

Additionally, as a center of urban development, Atlanta also suffers from unemployment issues which are comparable to the annual national unemployment rate near 5% (BLS, 2008). Thus, Atlanta as an urban region could potentially reap the social, economic and environmental benefits of altering its MSW stream management and post-consumer product EOL activities.

1.7 Analysis and Methodology

A modified Life Cycle Assessment (LCA) approach is used in this study. The LCA standards are based on those set by the International Organization for Standardization (ISO) in the ISO 14040 series (ISO, 1997). However, this study has been modified to include not only environmental impacts but social and economic impacts of each EOL scenario as well. Additionally, this study approaches the LCA from a waste-generation perspective. Waste generation begins an LCA with the end of a products primary use phase. The alternative would be to begin the LCA farther upstream with the acquisition of raw materials used to manufacture the product or with the deployment and primary use of the product. Any of the three perspectives would lead to identical comparative EOL assessments. However, for this study of EOL options and waste management practices, it makes sense to begin the assessment at the point where waste is generated. Cutting out upstream impacts that have no comparative impact alleviates much of the burden associated with acquiring the necessary data to compile life cycle inventories (LCI) for the upstream phases. Additionally, minimizing the data needed to adequately assess the impacts of a comparative study allows for a greater focus on the data that is collected and thus leads to greater confidence in the data obtained and assessments made. Thus, this study focuses on waste generation, waste collection, EOL activities, and replacements and/or "new" products that would be used in a second product use phase.

There are a myriad of PCC EOL scenarios that can be explored based on the variety of mechanical and chemical unit processes that transform carpet waste into something usable. Each unit process is examined individually for its direct environmental, social and economic impact within the PCC EOL framework under the guidelines of the modified LCA. Once each unit processes is defined, several combinatorial permutations will be examined in order to study the impacts of existing and potential PCC EOL scenarios in their entirety – from material reclamation to secondary product deployment. Here, the comparative study between EOL scenarios will provide insight into the realm of sustainability highlighting the inhibitors and enablers of material mining and the implementation of recycling networks in an urban environment from a social, economic and environmental perspective.

The specific categories chosen to represent the social, economic and environmental impacts of each EOL scenario considered are summarized in the following Table 1.2. The economic impact categories represent the primary operational costs associated with the EOL activities. The same operational impact approach is applied to the social impacts categories. The environmental activities, however, are chosen for a few different reasons. The greenhouse gases represent the operational impacts of the EOL activities on global warming potential, which is an every increasing environmental concern. The criteria air pollutants are chosen in order to gain a better perspective on the operational impacts associated with general air quality, specifically smog, which is a greater problem in urban regions due the continuous traffic. Lastly, the additional pollutants are chosen in order to gain some perspective on direct human health implications due to heavy metals such as lead and mercury in the air.

Table 1.2: LCA Impact Categories

<table>
<tr><th>Impact</th><th colspan="3">Category</th></tr>
<tr><td rowspan="12">Environmental Impact</td><td rowspan="3">Greenhouse Gases</td><td>carbon dioxide</td><td>CO_2</td></tr>
<tr><td>methane</td><td>CH_4</td></tr>
<tr><td>nitrous oxide</td><td>N_2O</td></tr>
<tr><td rowspan="3">Criteria Air Pollutants</td><td>sulfur dioxide</td><td>SO_2</td></tr>
<tr><td>nitrogen oxides</td><td>NO_x</td></tr>
<tr><td>carbon monoxide</td><td>CO</td></tr>
<tr><td rowspan="5">Additional Pollutants</td><td>volatile organic compounds</td><td>VOCs</td></tr>
<tr><td>mercury</td><td>Hg</td></tr>
<tr><td>hydrocarbon</td><td>HC</td></tr>
<tr><td>particulate matter</td><td>PM</td></tr>
<tr><td>sulfur oxides</td><td>SO_x</td></tr>
<tr><td>Solid Waste</td><td colspan="2">material waste</td></tr>
<tr><td rowspan="5">Economic Impact</td><td rowspan="2">Energy</td><td colspan="2">electricity</td></tr>
<tr><td colspan="2">diesel fuel</td></tr>
<tr><td rowspan="2">Material</td><td colspan="2">landfill tipping fees</td></tr>
<tr><td colspan="2">virgin material market price</td></tr>
<tr><td>Labor</td><td colspan="2">wages</td></tr>
<tr><td rowspan="3">Social Impact</td><td rowspan="3">Labor</td><td colspan="2">employees required</td></tr>
<tr><td colspan="2">potential employment hours</td></tr>
<tr><td colspan="2">labor wages</td></tr>
</table>

The comparative assessments will be based on the overarching impacts as a comprehensive aggregated interpretation of each specific impact category. The impact categories will be defined based on data gathered and assimilated from various databases, first-order principles, machine specifications and industry or generally accepted estimates. Thus, the primary analysis of this study is prescriptive in that it will include the adaptation of estimates and previous research in order to model the EOL scenarios for the comparative assessment. The prescriptive models will be validated with descriptive methods where they exist. In other words, some of the EOL scenarios considered have been previously studied, and the results of those studies will be used to verify the estimates and models created here.

1.8 Research Goals and Objectives

The goal of this thesis is to determine preferable EOL activities for PCC in the Atlanta Metropolitan Region. Additionally, the study will focus on the inhibitors and enablers of urban recycling based on the PCC EOL scenarios considered in the Atlanta Metropolitan Region. These goals will be achieved through an adapted comparative LCA, which will consider social, economic and environmental impacts of each of the EOL scenarios modeled. The goals will be achieved by first determining the general EOL scenarios to be considered and outlining the goal and scope of each scenario. Next, the phases of each scenario will be modeled independently in order to build the life cycle inventory (LCI) database necessary for conducting the study. Once the data is gathered and interpreted, the models will be assembled and the impacts determined. Finally, a comparative assessment will be conducted in order to determine the preferable EOL scenario(s) and the general barriers and successes of PCC urban recycling based on all three impact categories.

The issues spurring from the goals and objectives stated above lead to several questions regarding urban recycling and comparative EOL LCA studies. These questions, as well as the hypothesis for each, are summarized below.

Question 1: What is the environmentally preferred EOL scenario for PCC?

Hypothesis: A closed-loop recycling scenario is the most sustainable and consequently the environmentally preferred EOL option for carpet.

Question 2: What is the preferred EOL scenario for PCC based on a TBL assessment of the various EOL options? What are the compromises and trade-offs that must be made between environmental, social and economic impact categories?

Hypothesis: The three impact categories are intertwined, thus compromises must be made based on preferences and underlying assumptions made by the assessor. But again, the “closed-loop” recycling strategy would offer the most positive social, economic and environmental impacts.

Question 3: What are the major hurdles of each EOL scenario for PCC?

Hypothesis: When considering the differences between mining waste in urban regions and mining virgin materials for industrial use, the most prominent difference is the dispersion of materials. The mining of virgin materials for one product occurs in a handful of locations and the materials are shipped to one manufacturing facility. When mining waste in urban regions, bits and pieces of the materials needed are collected from individual households or businesses and then individually transported, or transported in small quantities, to the manufacturing facility. Thus, the actual collection and transportation of goods will be the largest burden to overcome when developing more sustainable urban recycling systems.

Question 4: Is the modified LCA used here offer a standardize method or procedure to comparatively assess the social, economic and environmental impacts of EOL scenarios?

Hypothesis: The modified LCA used here provides users with a method to quantitatively compare social, economic and environmental impacts in a way that isolates the impacts yet still highlights the interconnections between them. The modified LCA used here is by no means a completely comprehensive framework for assessment (in that it does not consider every single potential pollutant or fixed and capital costs associated with individual process or labor requirements of upper-management or auxiliary workers), but it does provide a baseline for studying EOL scenarios from a TBL perspective.

With these questions in mind, the structure of this thesis is as follows. This introductory chapter provides some of the motivation and greater context surrounding this study. Chapter 2 delves deeper into the background of LCA and includes a literature review summary of existing EOL and PCC studies. Chapter 3 focuses on the goal and scope of the comparative LCA and includes a definition of and bounds for each EOL scenario considered. Chapters 4 through 8 are used to build the LCI database for this study with individual chapters for product inventory estimates, electricity in Georgia, collection strategies and transportation, materials, and mechanical and chemical unit processes. The actual impact assessments are conducted in Chapter 9, and Chapter 10 contains the comparative assessments, highlighting the sensitivity of the results and the inhibitors and enablers of the various EOL scenarios. The study ends in Chapter 11 with conclusions, a recap of the research questions and hypothesis and closure for a broader impact and future work.

CHAPTER 2

BACKGROUND

2.1 Introduction to Life Cycle Assessment

This comparative study of EOL scenarios for PCC is conducted according to the LCA framework as outlined by the International Organization for Standardization (ISO) 14040: Environmental Management standards. The following diagram contains an outline of the general framework for analysis (ISO, 1997).

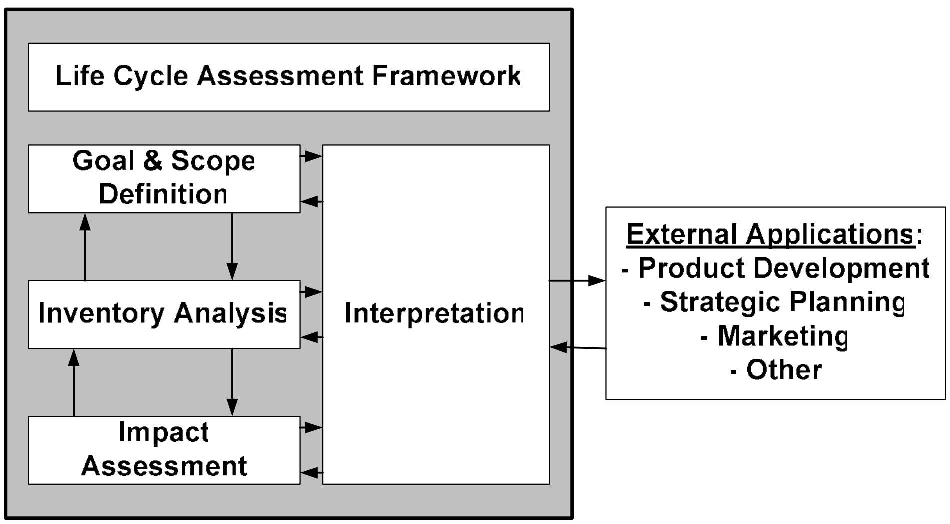


Figure 2.1: Life Cycle Analysis General Framework

A traditional LCA is conducted in five interconnected and iterative stages. The first stage includes the user defined goals and scope of the assessment. The second phase is comprised of an analysis of the information inventory of the current project. This is followed by an impact assessment. These first three phases are conducted in conjunction with a user interpretation of the current project, which may lead to iterations, changes or advancements with regards to the original goal and scope of the project. The LCA ends with an external applications stage in which the user reflects upon the assessment and offers these reflections as recommendations or awareness to the intended audience as outlined in the goal and scope phase (ISO, 1997).

This general LCA framework will be followed throughout the development of the study. However, a traditional LCA focuses only on the environmental impacts of material and energy flows throughout the scope of the project. Thus, the inventory analysis leads to LCIs that are generally filled only with environmental indicators of solid wastes and emissions into land, water and air. Inventory Analysis phase is augmented in this study, and consequently the following phases as well, by adding indicators for economic and social criteria. Thus, the overall impact will come in the form of a TBL assessment.

2.1.1 Goal and Scope Definition

The first phase of a traditional LCA begins with a statement of goals and bounds for the study. The goals of the study define the purpose, intended use, and audience. In other words, the goals of an LCA study are used to clearly state the limits and theoretical bounds of the results.

The scope of an LCA is used to outline the data requirements, limitation and physical boundaries of the system(s) being studied. The following list is an excerpt from Section 5.1.2: Scope of the Study in ISO 14040 series and identifies items to address in the scope of an LCA.

- the functions of the product system, or, in the case of comparative studies, the systems;
- the functional unit;
- the product system to be studied;

- the product system boundaries;
- allocation procedures;
- types of impact and methodology of impact assessment, and subsequent interpretation to be used;
- data requirements;
- assumptions;
- limitations;
- initial data quality requirements;
- type of critical review, if any;
- type and format of the report required for the study

Thus, the Goal and Scope Definition phase of an LCA is used to set the tone for the study. It includes an outline of objectives and defines the bounds of the systems being considered in order to help ensure uniformity in results for parallel impact comparisons. Because much of an LCA includes subjective assessments, it is important to set these bounds early in order to establish a protocol and procedures for handling issues that may arise during the study (ISO, 1997).

2.1.2 Inventory Analysis

The Inventory Analysis phase of an LCA involves all of the necessary research, data collection and calculations needed to build an LCI database of the product systems considered. The actual inventory collected is based on the defined Goal and Scope for the LCA taking into account items such as desired functional units, system boundaries, allocation procedures, impact categories to be assessed and data quality requirements. The data that comprises the LCI datasets can come from a myriad of sources and be represented in a variety of ways. For example, data can be acquired first hand through experimentation and observation, it can be calculated from theoretical equations, or it can include peer-accepted estimates. Thus, the Inventory Analysis phase involves the acquisition and definition of both qualitative and quantitative, theoretical and actual, data (ISO, 1997).

Since the LCA framework is augmented here by including within the bounds of the study the assessment of social and economic impacts as well, the first major changes to the traditional LCA appear in this phase. The Inventory Analysis in this study will not be completely uniform in functional unit or allocation procedures. It will not only include environmental indicators but the economics and labor potential associated with the product systems. Thus, not only will a dataset be created for the direct environmental, social and economic impacts associated with each process or phase of the product system, the augmented LCI will also include data that is meant to highlight the interconnections between each of the main impact categories.

2.1.3 Impact Assessment

The user of the study aggregates and interprets the various impact categories defined in the Goal and Scope of the LCA based on the data in the LCI database and aggregated in the Inventory Analysis phase. This phase includes a transformation of the modular data of the Inventory Analysis phase into a more comprehensive system representation of impacts in each category defined in the Goal and Scope. The transformations, however, can be subjective and thus must be clearly defined in order provide a more comprehensive representation of the transformation so that future users my duplicate the results (ISO, 1997).

The Impact Assessment of this LCA will be affected by the decision to augment the study with social and economic impacts in addition to the traditional environmental impact categories. Thus, transformations of the Impact Assessment phase will be rather intertwined in order to accurately capture the interconnections between social, economic and environmental impacts of the systems considered.

Environmental impacts are difficult to characterize due in part to their variability over time and space and the degree of cause-and-effect impacts that can result. In other words, the effects of a particular pollutant vary as time passes and as it disperses into the surroundings and along cause-and-effect chains such as the food chain. Therefore, it is helpful to aggregate the data in a way that better represents the effects of such environmental impacts and provides meaning to an otherwise incomprehensive list of pollution rates. The EPA developed the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) in an attempt to standardize the aggregation of environmental impacts for use in such studies as LCAs in an attempt to simplify the assessment given the difficulties mentioned. TRACI utilizes a midpoint analysis method, which means that the impact is assessed at a common midpoint along the cause-and-effect chain. This simplification eliminates some of the uncertainty associated with modeling and forecasting impacts at the endpoints with data that may or may not be available for all pollutants. The equivalencies used in TRACI seek to capture the major environmental and health concerns associated with a particular group of pollutants. Table 2.1 contains the equivalency units used in this study and their corresponding definitions as they related to environmental impacts. The actual equivalency values are discussed lager in Chapter 3 (Bare et al., 2003).

Table 2.1: Cause-effect Chain Selection (Bare *et al.*, 2003)

Impact Category	Function Unit	Midpoint Level Selected	Possible Endpoints
Global Warming Potential	CO_2-equivalents	Potential global warming based on chemical's radiative forcing and lifetime.	malaria, costal area damage, agricultural effects, forest damage, plant and animal effects
Human Health: Criteria Air Pollutants	microDALY[1]	Exposure to elevated particulate matter.	Disability-adjusted life-years (DALY), toxicological human health effects
Smog Potential	NO_x-equivalents	Potential to cause photochemical smog.	human mortality, asthma effects, plant effects
Ecotoxicity	g 2,4-D equivalents[2]	Potential of a chemical released into an evaluative environment to cause ecological harm.	plant, animal, and ecosystem effects

2.1.4 Interpretation

The Interpretation phase is an ongoing phase throughout the entire LCA. It encapsulates all interpretations of goal, scope, inventory and assessment and thus provides the framework for the iterative feedback loop used to modify and improve the study throughout the process. It is important to approach the Interpretation phase from the entire LCA perspective. The interpretations made by the user can take the form of conclusions, recommendations, observations, etc. so it is important to draw these conclusions from the aggregated impacts presented in the Inventory Assessment and considering both the raw data gathered and calculated in the Inventory Analysis and especially considering the context of the study as defined in the Goal and Scope. Again, this is an iterative and evolving process, so interpretation may lead to revisions and directional changes during the study. This flexibility helps to ensure that a more

[1] DALYs "account for years of life lost and years lived with a disability, adjusted for the severity of the associated unfavorable health conditions" due to the pollutants effecting human health (Lippiatt, 2002).
[2] The EcoToxicity impact "measure the potential of a chemical released into the environment to harm terrestrial and aquatic ecosystems … characterization factors for potential ecological toxicity use 2,4-dichlorophenoxy-ecetic acid (2,4-D) as the reference substance" (Lippiatt, 2002).

thorough and meaningful assessment be conducted based on information that may be received mid-study (ISO, 1997).

2.1.5 External Application

The External Application portion of the LCA is the final product stage of the assessment. It is in this phase that the findings of the study are presented or are represented per the original intent of the study as outlined in the Goal and Scope. This stage marks the end of the entire process, and thus must include the complete LCA package associated with the study. This is to ensure that not only are all the recommendations and conclusions available, but that all of the supporting material be included so that future users are able to fully understand the conclusions being drawn and are able to reproduce the results if necessary (ISO, 1997).

2.2 Introduction to Carpet

Carpet comes in a variety of sizes with varying material compositions based on use and performance specifications. Carpet is used in both commercial and residential settings and the characteristics of each are different. Commercial carpet is generally more durable and has a shorter face fiber in order to stand up to the heavy traffic of commercial use. Residential carpet, on the other hand, is softer with thicker cushioning and longer face fibers in order to appeal to bare feet and to add warmth and comfort to the home. The total carpet industry, including both residential and commercial types, generated approximately $13.9 billion at the mill level in 2005 with shipments totaling over 2 billion square yards. This includes overseas shipments and sales because the US carpet industry produces approximately 45% of the world's carpet (CRI, 2007). Around

90% of this carpet is tufted. The complete breakdown of carpet manufacturing techniques can be found in Figure 2.2. Additionally, the industry statistics for annual material consumptions based on 3.5 billion pounds of material is found in Figure 2.6.

2.2.1 Carpet Manufacturing

There are three predominant carpet manufacturing processes: tufted, needlepunched and woven. Figure 2.2 shows the percentage each process possesses within the total industry.

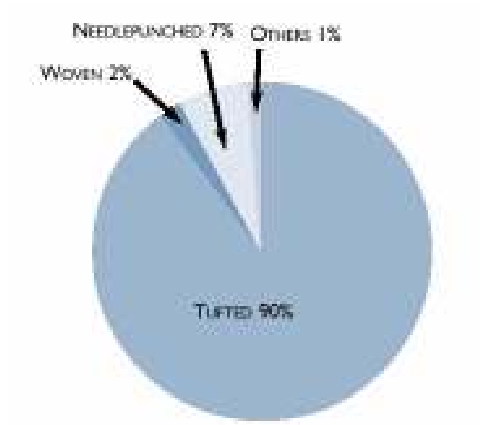


Figure 2.2: Carpet Manufacturing Processes (CRI, 2007)

Tufting, the predominant manufacturing process, is done on a specialized sewing-machine containing several hundred needles that push yarn through the primary carpet backing. The yarn is held in place by a loop; when the needle is removed, this forms the short tufted face fibers shown in Figure 2.3. The loops remain as is if the carpet is to be looped pile (Figure 2.4). After the face fibers are constructed, a secondary backing is applied in order to provide more structure and durability (CRI, 2007). Tufted carpet is found in both residential and commercial settings.

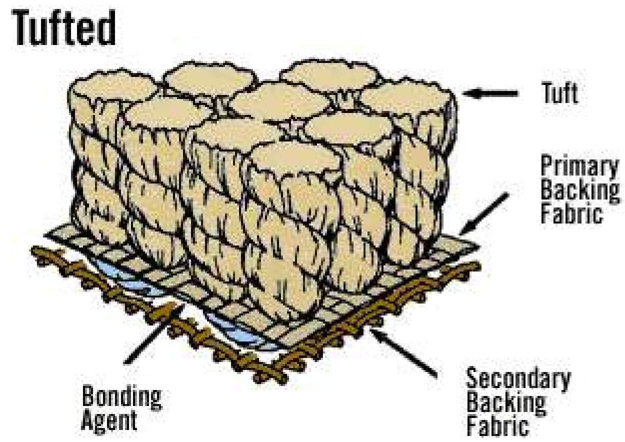


Figure 2.3: Tufted Carpet Composition (CRI, 2007)

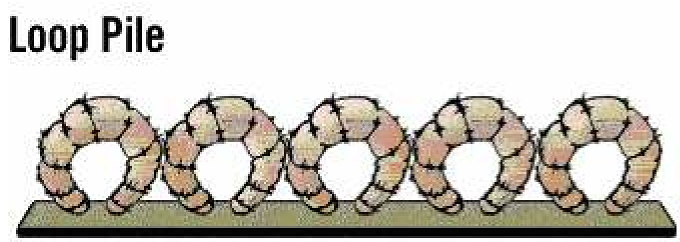


Figure 2.4: Loop Pile Carpet (CRI, 2007)

Woven carpet is created on looms. Face fibers and backing yarns are simultaneously interlaced into a complete sheet of carpet. Because the weaving itself creates a complete carpet, no additional backing is added to the woven fibers; however, a small amount of latex adhesive is generally added to the underside to provide some support and protection from unraveling. Figure 2.5 contains an illustration of the cross-section of woven carpet. Woven carpet is generally only found in commercial settings (CRI, 2007).

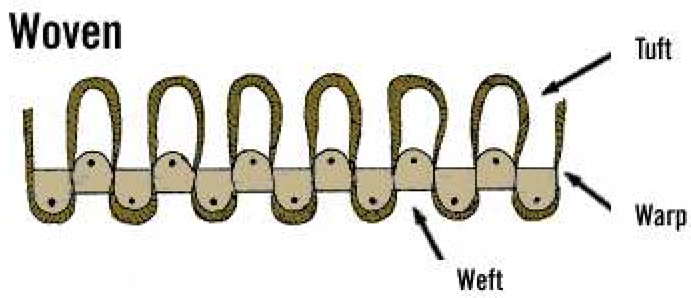


Figure 2.5: Woven Carpet Composition (CRI, 2007)

Needlepunched carpet is manufactured with barbed needles that literally punch the face fibers through a sturdy, vinyl, backing material and is then sealed with a latex substance. This method allows for cheap manufacturing of patterned or textured carpets. The needlepunch method is used mainly for indoor-outdoor carpeting or artificial grasses. Additionally, this kind of carpet is geared more towards a commercial setting given its shorter face fibers, sturdy construction, and cheaper manufacturing techniques (FloorBiz, 2008).

In addition to the major methods of carpet manufacturing, carpet generally comes in two kinds of stock – **broadloom** and **carpet tile**. Broadloom carpet comes in three main sizes: 12ft, 13.5ft, and 15ft in width (approximately 3.66m, 4.11m, and 4.57m respectively). It is easy to install in large areas with few seams, depending on the size of the room being carpeted and the width of the carpet selected. Traditionally, broadloom compromises the vast majority of the residential carpet sector and a smaller percentage of the commercial carpet sector (CRI, 2007). Carpet tile, on the other hand, is primarily designed for commercial use only, although several options do exist for the homebuyer. It comes in 0.5m square tiles and a variety of colors and patterns to suite all decorative needs. Carpet tiles have durable face fibers and a sturdy polyvinylchloride (PVC) backing. The benefits of carpet tile include localized replacement for wear and tear or stains and easier installation with less installation waste (InterfaceFLOR, 2007).

2.2.2 Carpet Fibers and Materials

The US carpet industry uses approximately 3.5 billion pounds of material for face fibers annually. Figure 2.6 shows the breakdown of the face fiber material used by the entire industry in a year.

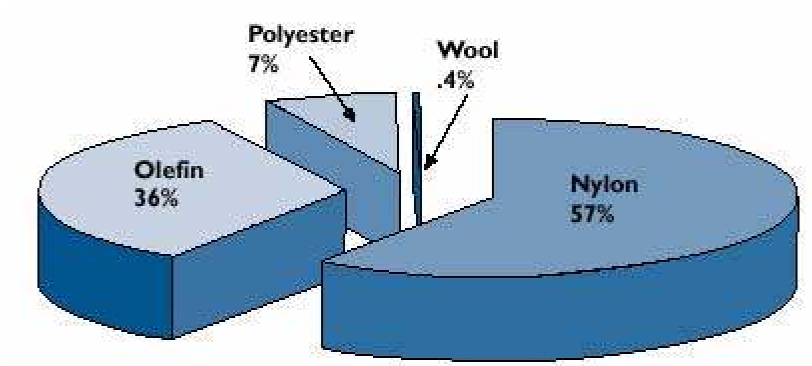


Figure 2.6: Annual Fiber Consumption - 3.5 billion pounds (CRI, 2007)

Nylon fibers dominate the market in both residential and commercial carpet sectors. Approximately 80% of the commercial market and about two-thirds of the residential market are comprised of Nylon face fibers. Nylon is an ideal material for carpet because it is durable, stain resistant and holds vibrant colored dyes (CRI, 2007). There are two types of Nylon used in the carpet industry: Nylon 6, and Nylon 6,6. Nylon 6 was created in order to compete with the original Nylon 6,6 patent. The two types of nylon are similar their durability, resilience and resistance to stains and mildew. However, the two differ in that Nylon 6 is easier to dye and generally a little cheaper.

Olefin, or **polypropylene** (PP), comprises around 8-10% of the commercial market and a small percentage of the residential market. It is used in commercial settings when resistance to color fading is more important than durability. However, PP can be used both indoors and outdoors due to its high resistance to moisture and mildew; thus, PP is the fiber of choice for synthetic turf on athletic fields or for patio carpet (CRI, 2007).

Polyester, used mainly in residential carpets, offers the plush-ness and comfort expected in home carpet. It is used to make the lush thick, cut-pile carpet. Additionally, polyester has excellent color retention and is stain resistant (CRI, 2007).

Wool, the only natural fiber used in carpet composition, makes up about 8% of the commercial market and 3% of the residential market. Wool carpet is generally more expensive than its synthetic counterparts, but it is soft and luxurious and comes in a multitude of colors and patterns. It is highlighted in commercial use for its ability to self-extinguish if caught on fire. However, because of the higher price, wool carpet is usually only used as a decorative accent in low traffic areas (CRI, 2007).

Carpet Backing is generally comprised of a primary backing, sometimes a secondary backing depending on use environment, a chemical adhesive, and filler. The primary backing is the fabric into which the face fibers are woven and is generally made of **PP**. The secondary backing is adhered to the primary backing with a chemical adhesive in order to provide some structure and stability to the whole carpet package for use in high traffic or heavy wear areas. This type of backing is usually made of a stiffer, more durable plastic such as **PVC**. The filler, mixed in with the two backings, is usually comprised of **calcium carbonate** ($CaCO_3$) which provides some additional cushion and support (CRI, 2007).

2.2.3 Carpet Composition

Broadloom weighs approximately 2.2kg/m^2 and is comprised of face fibers, a PP primary backing, $CaCO_3$ filler, a styrene-butadiene latex adhesive (SBR) and a PP secondary backing. The generalized breakdown of material composition by weight for a typical broadloom carpet is found in Table 2.2 (Wang, 2006).

Table 2.2: Broadloom Material Composition

Material:	% composition	Function:
Face Fibers (Nylon, Polyester, Wool)	46%	face fiber
PP	10%	primary and secondary backing
$CaCO_3$	35%	filler
Latex Adhesive	9%	secures backing to face fibers

Carpet Tile weighs approximately 4.17kg/yd^2 (5kg/m^2) and is generally comprised of Nylon 6, polyethylene terephthalate (PET), fiberglass, PVC, poly(methylacrylate-co-vinyl chloride), poly(ethylene-co-vinyl acetate) (EVAC) copolymer, diisoheptyl phthalate, and $CaCO_3$. The breakdown of carpet-tile composition by weight is outline in Table 2.3 (Realff *et al.*, 2004).

Table 2.3: Carpet Tile Material Composition[3]

Material:	% composition	Function:
Nylon 6	15%	face fiber
PET	3%	primary backing
Fiberglass	1%	primary backing reinforcement
PVC	5%	secondary backing material
Poly(methylacrylate-co-vinyl chloride)	7%	backing additive
EVAC copolymer	6%	adhesive
Diisoheptyl phthalate	12%	backing additive (for flexibility)
$CaCO_3$	50%	backing filler

[3] Percentages may not equate to one hundred due to independent rounding.

Although carpet is generally referred to by its face fiber material, there are clearly other materials, some with value and some nearly valueless, incorporated into the carpet. This material mix creates some difficulty when recycling carpet as it generally complicates the process of recapturing the valuable recyclable material. Table 2.4 below summarizes the industry trends of carpet material composition by broadloom and carpet-tile.

Table 2.4: General Carpet Composition

Carpet Component	Material	Broadloom	Carpet-Tile
Face Fibers	N6	**X**	**X**
	N6,6	**X**	
	PP	**X**	
	Polyester	**X**	
	Wool	**X**	
Backing	PP	**X**	
	PVC		**X**
Filler	$CaCO_3$	**X**	**X**
Adhesives	SBR	**X**	
	EVAC		**X**

2.2.4 Post-Consumer Carpet End-of-Life Options

Carpet is a complex composite material and thus lends itself to a myriad of EOL options based on the specific material composition. Below, in Table 2.5, is a summary of the EOL options for the various carpet materials discussed earlier in this chapter. This table does not include all of the carpet materials because many of the materials have no recycling potential or do not hold enough of the market share to make recycling the materials practical.

Table 2.5: Generalized End-of-Life Options for Post-Consumer Carpet

EOL Option	N6	N6,6	PVC backing	Notes:
Waste Disposal (WD)	X	X	X	baseline scenario for all materials
Repurpose Material Reclamation (RMR)	X	X		re-use of entire PCC, thus re-using of all materials
Primary Material Reclamation (PMR – PVC, N6)	X		X	**PVC**: PCC-tile backing back into backing **N6**: face fibers back into original N6 monomer/caprolactam
Secondary Material Reclamation: Material into Pelletized Plastics (SMR – N66)		X		**N6,6**: create pelletized plastics for use in extruded or compression molded auto parts
Secondary Material Reclamation: Materials into new Product (SMR-underlay)	X	X		broadloom carpet recycled into carpet underlay

2.3 Literature Review - Carpet Waste Management and End-of-Life Studies

Because PCC is such a relatively large portion of the overall MSW stream in the US, an industry wide initiative had been organized to reduce the overall amount of PCC sent to landfills and several studies have been conducted in order to explore the implications and possibilities of various waste management policies and EOL alternatives. The industry wide initiative began in 2002 with the signing of the Memorandum of Understanding for Carpet Stewardship (MOU) by industry, government and non-governmental organization representatives. The overarching goal of the MOU is for carpet manufactures to assume the necessary responsibility needed to divert 40% of all used carpet from landfills by 2012. C.A.R.E. was formed out the MOU as a third-party organization dedicated to uniting the efforts among carpet manufactures, recyclers and entrepreneurs alike in order to achieve the landfill diversion goals and to encourage alternate EOL uses for PCC. To date, C.A.R.E has estimated that over 1 billion pounds of carpet have been diverted, of which 275 million pounds were diverted for recycling in 2007. And, in order for these numbers and rates to continue to increase C.A.R.E. is continuing to do its part in organizing the players in PCC management and is helping to foster new industries focused on utilizing PCC as its input (CARE, 2006).

The EPA is also focused on the impact of PCC on the MSW stream. It included PCC as part of its 2006 revised report *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. The goal of the report was to identify the GHG emissions and the GWP of several waste management options as compared to a baseline scenario of product disposal in a landfill without energy capture. The EPA study included the effects of source reduction, combustion, open-loop recycling, and landfilling with energy capture. PCC, in this case, was aggregated based on national carpet industry statistics for material compositions and secondary products produced from PCC (EPA, 2006). Thus, the PCC waste stream considered assumed that carpet face fiber mix was 45% Nylon 6 and 55% Nylon 6,6, carpet backing was made of PP, and latex was used to adhere the carpet backing to the face fibers with fillers consisting solely of $CaCO_3$. The mix of secondary products was assumed 67% carpet pad/cushion, 25% molded auto parts and 8% carpet-tile backing (EPA, 2003). For each waste management scenario considered, the GHG emissions were derived from national emissions reported for industry averages of process energy, transportation energy, and process non-energy required by each phase of the EOL scenario considered. Because of the nationally generalized statistics used, there exists the potential for great discrepancies between local impacts and the impacts reported in the study (EPA, 2006). The results of the EPA study indicate Carbon Equivalent emission savings for source reduction and recycling and increased emissions for combustion and landfilling as compared to the baseline of PCC disposal without energy capture (EPA, 2003).

Another PCC LCA article was published by Lave et al. in a 1998 issue of the Journal of Industrial Ecology titled *Recycling Postconsumer Nylon Carpet: A Case Study of the Economics and Engineering Issues Associated with Recycling Postconsumer Goods*. Lave et al. focus on the collection, sorting, handling and storage of all PCC while concentrating only on the recycling of Nylon carpet. The results are centered on the economic barriers of the entire recycling scheme and the engineering concerns regarding the manufacturing of recycled content materials for sale. Most of the carpet data is aggregated from national averages while the economics of operating a carpet recycling facility are based on the costs of an existing facility in Pittsburgh, Pennsylvania. The recycling scenarios considered are carpet shredding to be used in concrete application or landfill covers, recycling face fibers into high-value plastics, and recycling the entire carpet into low-value plastics. The results of the study indicated that the only economically viable option is the recycling of commercial carpet into Nylon 6 feedstock and Nylon 6,6 pellets. The dominating barrier for every recycling scenario proved to be collection costs (Lave, 1998).

Although the EPA and Lave et al. studies expose some of the pros and cons of PCC waste management and recycling, neither study offers a comprehensive assessment of the sustainability issues of the EOL scenarios based on social, economic and environmental impacts. The EPA study fails to consider any economic issues associated with waste management options while Lave et al. completely ignore the environmental impacts of recycling PCC. It can be argued that each study implies, to some extent, social impact based on environmental impacts in the EPA study and labor costs in the Lave et al. article. However, neither explicitly explores any social implications of the various EOL scenarios considered.

Additionally, both studies use nationally aggregated data to represent economic and environmental impacts of the waste management and recycling scenarios considered. This kind of aggregation can lead to significant discrepancies when considering the local impacts of life-cycle EOL assessments. For example, transportation energy and collection costs, both significant economic and environmental impact categories, vary a great deal by distances traveled and local fuel costs. Both factors, distance and fuel costs, vary a great deal by geography; thus, this major barrier of waste management has a wide swing of impact when considering the local variances.

2.4 Life Cycle Inventory Databases

Several government organizations, private consulting firms, and universities have developed software systems, tools, and databases in an effort to gather, capture and store in an accessible and meaningful format environmental information regarding commonly used industrial materials and practices. Several of these databases were used in this study as a means to gather input/output information, energy flows, and environmental impacts associated with materials and processes existing in the EOL options explored. Where multiple datasets were available for any given material, they were compared against each other and assumptions were made in an attempt to reconcile the differences. In order to better understand the datasets available for use, it is important to know a little bit about the databases themselves. This section contains brief introductions to the databases used in this study.

2.4.1 The National Renewable Energy Laboratory Online Database

The National Renewable Energy Laboratory (NREL) online database is a life cycle inventory database specializing in material and energy flows for a variety of common unit processes. The database was developed by the Athena™ Sustainable Institute out of Ontario, Canada; however, it is designed as a U.S. LCI database. This database focuses on individual process and materials and thus must be aggregated by hand in order for a user to build comprehensive dataset for final products or processes. The data itself is gathered from primary industry sources and from government published records. The raw data is presented in spreadsheet form with the additional implementation of some environmental equivalencies, through the TRACI tool, for easier assessments. The dataset is publicly available and searchable online at http://www.nrel.gov/lci/database/ (Torcellini and Deru, 2004). The NREL LCI database is used in this study to as a source of environmental impacts associated with some of the virgin materials used in the various EOL scenarios.

2.4.2 Building for Environmental and Economic Sustainability

The Building for Environmental and Economic Sustainability (BEES) software is a life cycle assessment tool developed by the National Institute of Standards and Technology Building and Fire Research Laboratory. The free software package is designed as a decision support tool to for building decisions taking into account the environmental and economic burdens of over 230 building products and over 500 material and energy flows. The software itself is windows operated and easy to navigate by streamlining choices based on end products. However, the assessment is transparent in that each life cycle stage is assessed individually and as an aggregated whole over the products entire life cycle. Additionally, environmental impacts are expressed in both TRACI formatted equivalencies and individual pollution statistics. The following figure depicts the general flow of information and data within the program leading to an ultimate score, which takes into account both environmental and economic indicators. As the figure supports, although the final score is an aggregated number, it is easily retraceable back to its initial data input roots (NIST, 2007).

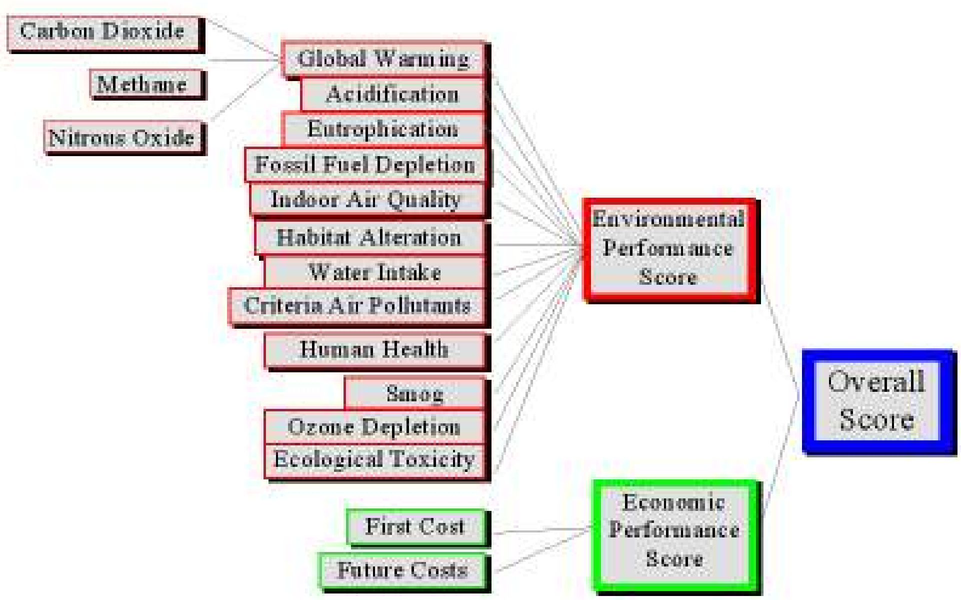


Figure 2.7: BEES Information Flow Diagram (NIST, 2007)

In this study, the BEES® Version 4.0e – August 2007 software is used for characterizing the environmental and economic impacts associated with such building products as broadloom carpet and carpet padding and services including carpet maintenance and cleaning. Thus, the BEES software is good for finished products, building materials, and building maintenance. The product descriptions offer general insight into the assumptions and processes contributed to the environmental and economic impacts of the various life cycle phases used to make the ultimate assessment. Additionally, the data is presented in both charts and spreadsheet format, so it is easy to interrupt and digest. One drawback, however, is the fact that the impacts are aggregated over a product's entire life. Thus, if a study requires data for only a portion of the product life cycle, it must be disaggregated by hand.

2.4.3 SimaPro

SimaPro is another LCA software kit designed by Product Ecology (PRé) Consultants. The SimaPro software not only includes LCI data for a variety of materials and processes, but it can be used to aggregates systems of materials and process activities inorder to assess an entire system. Additionally, the software is capable of parameterized modeling and simulated uncertainty analysis. Although all of these advances capabilities exist as part of this software packages, SimaPro was used solely as an LCI database in this study. The environmental information obtained is compared to the data from other databases in order to verify its validity and significance with in the more localized boundaries of this particular LCA study (Consultants, 2008).

2.4.4 IdeMat

IdeMat is an environmental assessment software tool developed by Delft University of Technology and copyrighted in 1998. The software was designed to store easily accessible technical information for both materials and processes with an emphasis on environmental factors. In addition to the environmental impacts and material and energy flows, the database also includes a characterization of the material or process that includes such information as mechanical and chemical properties. In total, each material and process is described in about forty different terms. In addition to the raw information available in the database, aggregated environmental indicators, such as Eco-and EPS-indicator scores, are included. These indicators offer a quick method for comparison that can be used to asses the relative environmental impacts of a variety of materials and processes. One major drawback of this database with regards to this study is that all of the data draws from European standards and averages, which means that some of the data may not be a valid or accurate representation of U.S. practices. Because of these potential discrepancies, the data from this database is compared to data from other databases in order to obtain average and more meaningful LCI data for this study (TUDelft).

CHAPTER 3

POST-CONSUMER CARPET END-OF-LIFE COMPARATIVE ASSESSMENT

There are several general EOL scenarios currently available for PCC. These overarching categories include: repurpose material reclamation (RMR), primary material reclamation (PMR), secondary material reclamation (SMR), and waste disposal (WD). Chapter 2.4 will outline the general goal and scope of the entire comparative LCA EOL study and then delve into the definitions and boundaries of each the individual EOL scenarios that will be comparatively assessed in Chapter Ten.

3.1 Goal and Scope

Goal of Study: The goal of this study is to determine a preferable EOL scenario for PCC in the Atlanta Metropolitan Region based on an individual EOL scenario's local social, economic and environmental impacts. Additionally, the goal is to identify and address the major inhibitors and enablers of the various EOL activities for PCC in the Atlanta Metropolitan Region in order to gain insight into PCC waste management and to define spaces for improvement. The EOL scenarios will be assessed based on the aggregated effects of individual processes and phases of each of the scenarios studied. Identifying the inhibitors and enablers will be conducted by ranking each process or phase according to its social, economic and environmental impacts.

Bounds of the Study: A waste generation approach has been chosen for this study. This implies that each EOL scenario will begin at the point of waste generation from primary product use. From this point, each scenario will then include the individual processes required to collect and transform the PCC from its PC-waste state into a useful secondary product as defined by the particular EOL scenario. For example, a PMR scenario could include the collection of PCC-tile and its transformation to re-usable PVC pellets for use in “new” carpet-tile backing versus a waste disposal scenario which would include the collection of PCC-tile and its proper disposal plus the acquisition of virgin PVC for use in new carpet-tile backing. Therefore, even if the particular EOL scenario does not include a transformation of recaptured material for re-use, a secondary product must be acquired in order to complete the EOL scenario and provide uniform or comparable boundaries for a comparative assessment. Refer to Figure 3.1 for a representation of the general bounds, inputs, and outputs of this comparative assessment.

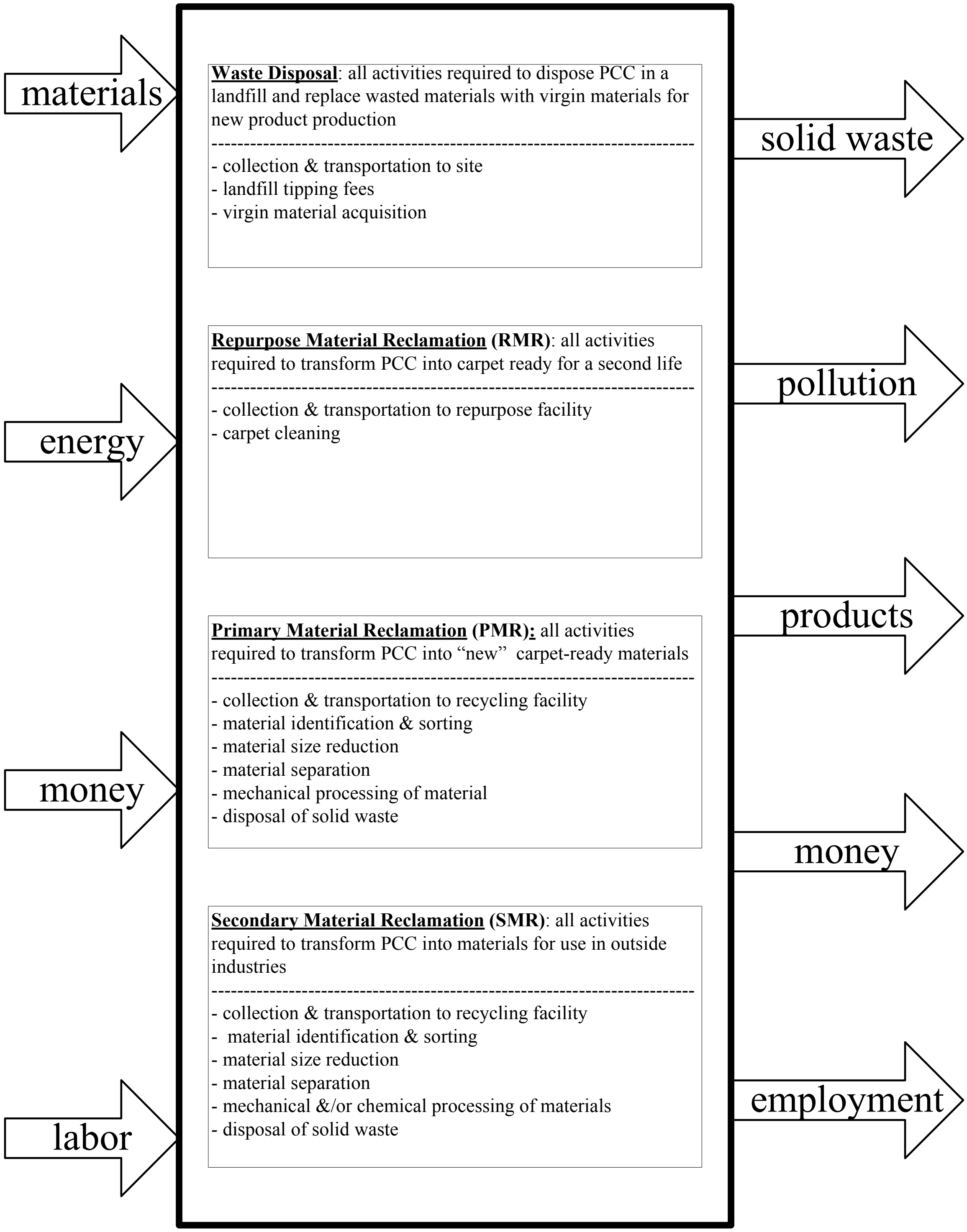


Figure 3.1: Inputs, Outputs and System Boundaries

Scope of the Study: This comparative assessment is designed to highlight the inhibitors and enablers of various PCC EOL scenarios in three impact categories –

environmental, social, and economic. These three categories are rather intertwined. They overlap in data requirements, can require trade-offs and compromises, and have some areas of unique impact. But, all together, they capture the scope of the study. Figure 3.2 is a Venn Diagram capturing the scope of this study and highlighting the interconnections between the three impact categories.

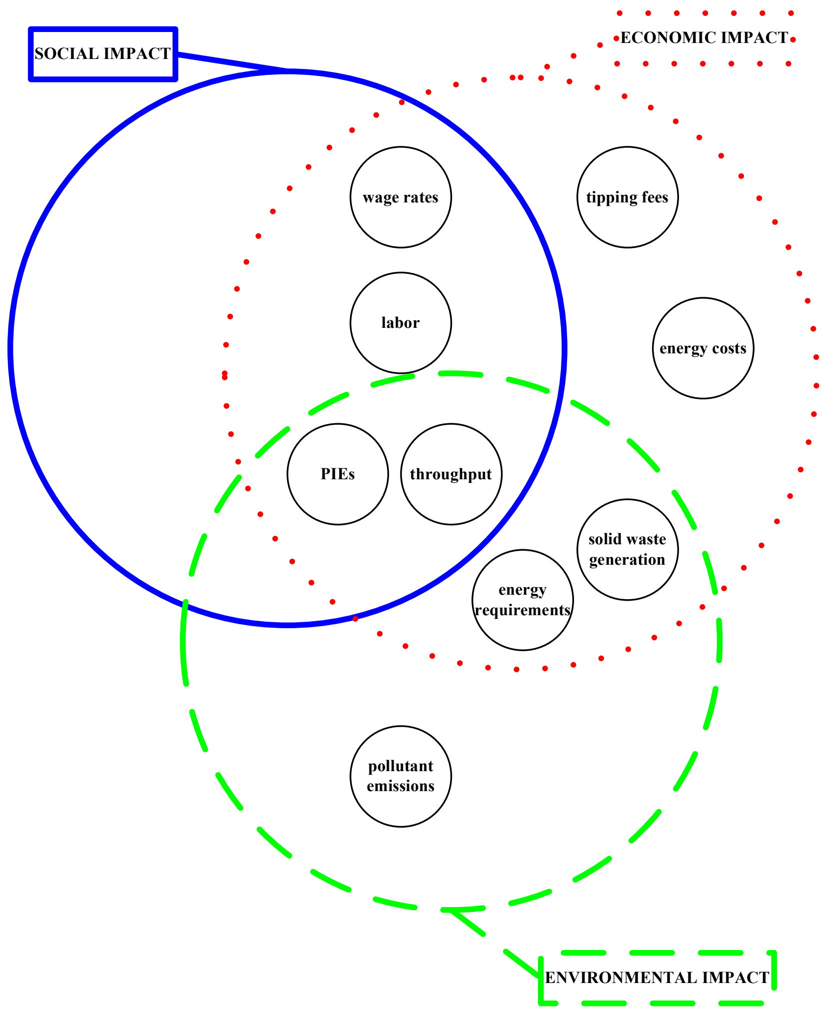


Figure 3.2: Interconnections of Impact

Type of Information Needed: This study is augmented to include social and economic impact categories in addition to the existing environmental impacts considered in a traditional LCA; thus, the information required to conduct the comparative study is of varying natures. The gross inputs to each scenario studied are material, energy, labor, and money. Therefore, for each process considered, the four inputs must be defined. On the other end, the gross outputs are solid waste, pollutant emissions, employment potential, money and products; thus, each of these must be defined as well for every process considered. In addition to the gross inputs and outputs, individual process efficiencies and throughputs must be defined. Efficiencies and throughputs help to capture the time requirements of each process, which will be used to appropriately translate gross inputs into outputs in a relative time scale. Thus, the information needed to obtain the desired outputs for impact analysis, which are summarized in Table 3.1, will vary according to the particular process and dataset.

Table 3.1: LCA Impact Categories

Impact	**Category**		
Environmental Impact	Greenhouse Gases	carbon dioxide	CO_2
		methane	CH_4
		nitrous oxide	N_2O
	Criteria Air Pollutants	sulfur dioxide	SO_2
		nitrogen oxides	NO_x
		carbon monoxide	CO
	Additional Pollutants	volatile organic compounds	VOCs
		mercury	Hg
		hydrocarbon	HC
		particulate matter	PM
		sulfur oxides	SO_x
	Solid Waste	material waste	
Economic Impact	Energy	electricity	
		diesel fuel	
	Material	landfill tipping fees	
		virgin material	
	Labor	wages	
Social Impact	Labor	employees required	
		potential employment hours	
		potential labor wages	

Required Data Specificity: The localized nature of this study and the relatively new methods and processes utilized by several of the EOL scenarios creates an interesting variety of specificity requirements. Because the study concentrates on PCC EOL options in the localized area of the Atlanta Metropolitan Region, the LCIs must be tailored to represent the local industrial atmosphere. Therefore, electricity use must be adapted to accurately represent the power supply of the state electricity grid. Additionally, transportation data regarding distances traveled should accurately represent travel on local roads and between actual locations within the region. The money required as input into the various processes for labor, energy and material costs must also reflect the local market. However, since this study includes EOL options that are currently being developed or are just emerging, some of the process data (energy inputs, throughputs and efficiencies) may be specific to one particular company or machine. This data, although limited in scope, will be extrapolated to represent what could become industry standards with regards to the particular process being discussed. A summary of the various levels of specificity is found in Table 3.2. Because the levels of specificity will vary according to category and data component, the specificity of each data set will be clearly defined in the LCI database, which can be found in Chapters 4 through 8.

Table 3.2: Levels of Data Specificity

Level of Data Specificity:	Examples of Data Type:
Localized Data	- transportation distance - energy grid - labor wages - fuel prices - product inventory estimates
Validated Estimates (with multiple datasets)	- material environmental impacts - material market prices - machine specifications
Theoretical Estimates (first order equations)	- fuel emission estimates - machine energy requirements
Expert Opinion	- PIEs - carpet composition - fuel consumption - percent truck loads
Estimated Ranges (simulate uncertainty)	- PIEs - transportation distances - percent truck loads - process efficiencies - material prices

Organization and Display of Data and Results: Data will be displayed in the LCI datasets by the appropriate functional unit. Generally, this functional unit will be transformed to an impact (dollars, grams of pollutant, grams of waste, labor hours, energy, etc.) per kilogram recyclable material. The individual datasets will remain as generic and adaptable as possible given the particular category or process; this is to make the transformations from LCI to Impact Assessment as easy and uniform as possible. Thus, the datasets should be displayed in a way that allows for the specified inputs (material, energy, labor, money) to be transformed into the desired outputs (pollutant emissions, solid waste, products, employment potential, economic costs). Refer to Figure 3.1 in order to gain perspective as to the relative inputs and outputs for each EOL scenario within the scope of this comparative assessment. Additionally, it is important to keep in mind the three impacts – environmental, social, and economic – being considered here. Thus, every dataset must include data that contributes to these impact categories, even if the impact is zero, so that a uniform comparative assessment can be made across all processes and scenarios.

In addition to the straightforward presentation of data, the comparative assessment will also be augmented with aggregated environmental impact categories such as Global Warming Potential (GWP) with a functional unit of g-CO_2 equivalent per kg-recyclable material, Smog Potential that has a functional unit of g-NO_x equivalent per kg-recyclable material, Human Health: Criteria Air Pollutants (CAPs) with a microDALY per kg-recyclable material unit and Ecological Toxicity (EcoToxicity) on a g 2,4-D per kg-recyclable material. These equivalencies were developed by the EPA for use in their Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). The purpose of TRACI is to provide a system of metrics and standards in order to create a uniform basis for the comparing of environmental impacts during an LCA. For more information about TRACI and how the equivalencies are determined, please refer to Section 2.1.3. The equivalencies used here to aggregately represent the environmental impacts are outlined in Table 3.3 -

Table 3.6 (EPA, 2008) (NIST, 2007).

Table 3.3: Global Warming Potential Equivalents

Pollutant	CO_2-equivalent
CO_2	1
CH_4	23
N_2O	296

Table 3.4: Criteria Air Pollutants Equivalents

Pollutant	microDALY
NO_x as NO_2	0.002
SOx as SO2	0.014
PM	0.046

Table 3.5: Smog Potential Equivalents

Pollutant	NO_x-equivalent
NO_x as NO_2	1.24
HC	0.968
PM	0.046

Table 3.6: Ecological Toxicity Equivalents

Pollutant	g 2,4-D-equivalent
Hg	118758
Pb	12.32
CO	0.02

3.2 Waste Disposal: Landfill – Baseline Scenario

Currently, the vast majority of PCC is disposed of in landfills. Thus, the landfill EOL scenario will serve as the baseline for all comparisons. It applies to all carpet, broadloom and carpet-tile, and all carpet materials that could potentially be recycled, namely Nylon 6, Nylon 6,6 and PVC. In order to maintain uniform system boundaries and functional units for comparisons, the Waste Disposal: Landfill Scenario will include the social, economic and environmental impacts associated with the acquisition of virgin materials to be used as inputs in the manufacturing of the secondary product to be produced. The quantity of virgin materials purchased will equal that to the quantity of equivalent material that is dumped in the landfill.

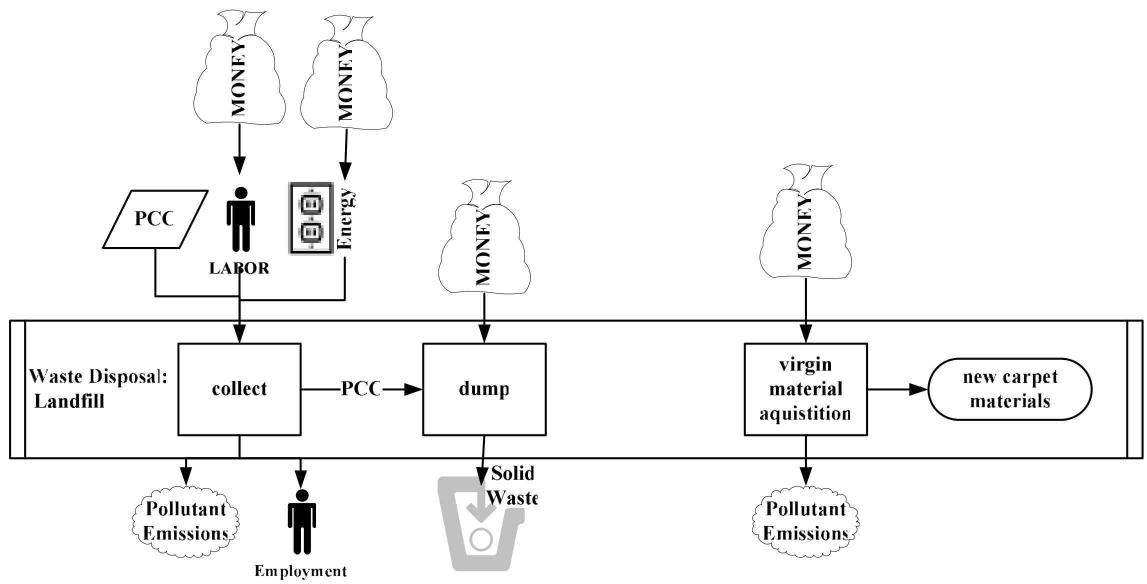


Figure 3.3: Waste Disposal - Landfill Scenario

3.3 Repurpose Material Reclamation

Repurpose material reclamation is defined as the collection and reuse of a material in its original capacity without any mechanical or chemical transformation. In this case, repurpose material reclamation involves the collection and cleaning of PCC for re-installation and use as a second generation floor covering. The repurpose material reclamation EOL scenario for PCC in the Atlanta Metropolitan Region is defined in Figure 3.4. It is assumed in this study that only broadloom carpets have the potential to be repurposed. PCC-tile is not likely to be repurposed because carpet-tile is durably designed and replaced tile-by-tile as the wear of the carpet demands. Thus, it is unlikely that an entire tiled area would be replaced at one time and in a condition suitable for repurposing. Thus the PIEs for PCC availability, style, and material composition will be based on the industry statistics for broadloom carpet only.

For the comparative assessment, in addition to the baseline landfill scenario, this RMR EOL scenario will be juxtaposed with the manufacturing of new broadloom carpet from virgin materials. This type of EOL scenario can thus be considered a source reduction scenario meaning that the amount of virgin materials needed to produce usable carpet are reduced by the fact that old carpet is being used in place of the new carpet. However, both of these scenarios, landfill and source reduction, are likely to exist in an economic red because repurposed carpet is generally donated for its second life. Thus, it has potential tax benefits, but no direct economic profit. Although, it is important to study considering that the environmental trade-offs could prove insightful and perhaps lead to the production of more durable and longer-lasting carpet.

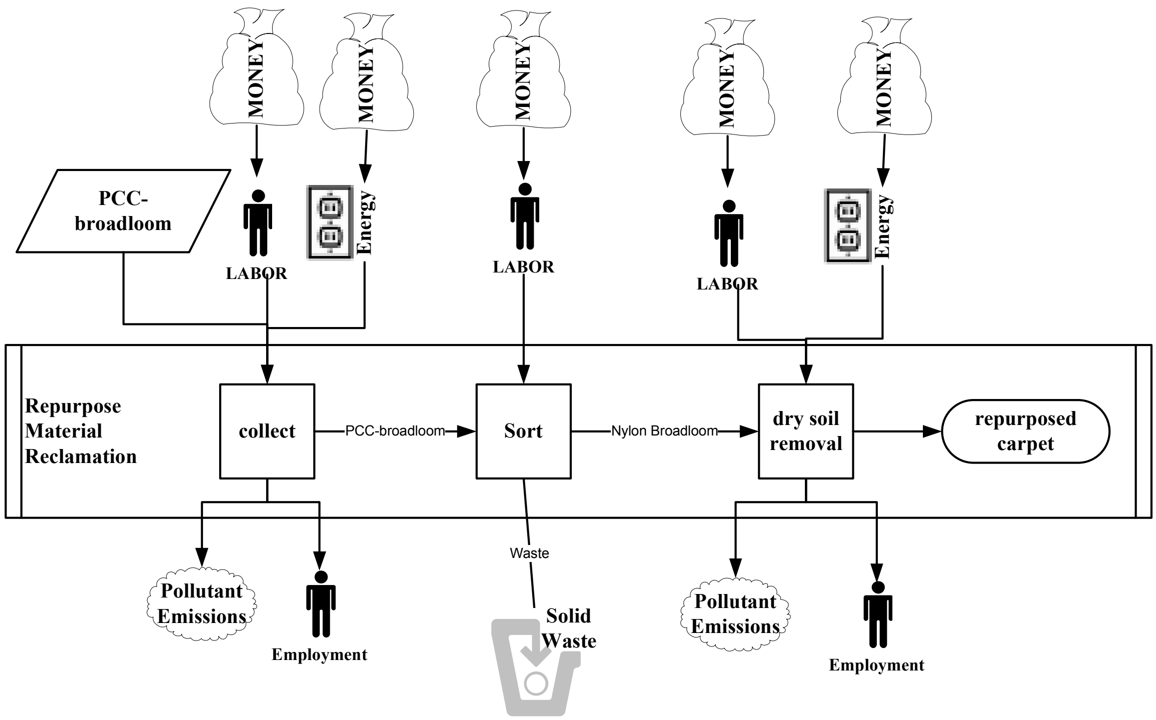


Figure 3.4: Repurpose Material Reclamation Scenario - Broadloom

3.4 Primary Material Reclamation

Primary Material Reclamation involves the collection of PCC and the recycling of the materials for use back into a new product with the same function. In other words, PMR is a closed-loop recycling chain where PCC materials are turned back into materials to be used in "new" carpet. For this study, the study considers two different PMR scenarios. The first scenario, outlined in Figure 3.5, involves PCC-tile and the recapturing of the PVC backing materials for recycling into PVC-backing pellets to be used in the backing of new carpet-tiles. This first scenario, the PCC-tile recycling, is currently only preformed at Interface's facilities in LaGrange, GA. The second scenario, described in Figure 3.6, is designed to recapture the Nylon 6 face fibers from PCC-broadloom. The Nylon 6 is then mechanically and chemically processed into its N6 monomer – caprolactam, which can be used to make Nylon face fibers for use in new broadloom carpet. Currently the recycling of Nylon 6 fibers takes place at Shaw's

Evergreen Facilities in Augusta, GA. In the baseline scenario for both of the PMR EOL options, it is assumed that the PCC materials not being recycled are disposed of in a local landfill.

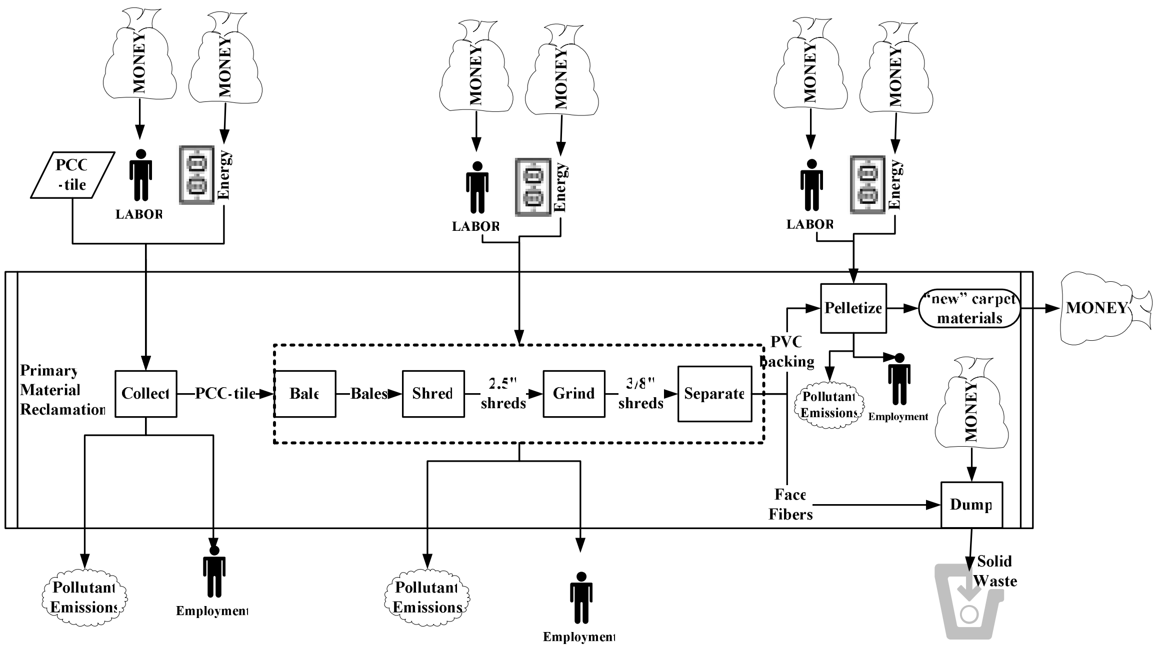


Figure 3.5: Primary Material Reclamation Scenario – Polyvinylchloride

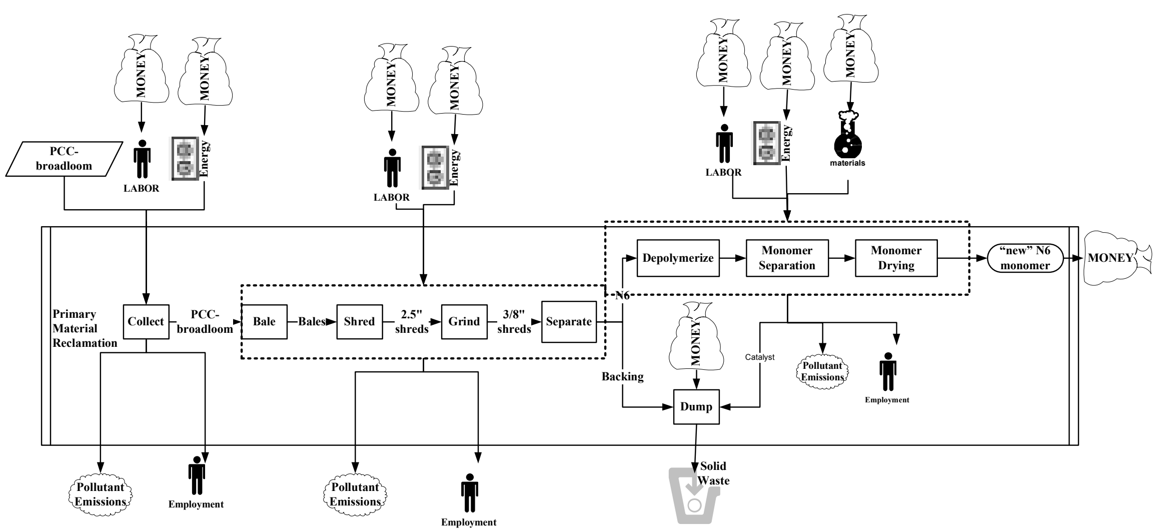


Figure 3.6: Primary Material Reclamation Scenario – Nylon 6

3.5 Secondary Material Reclamation

SMR, or "open loop" recycling, includes the collection of PCC and its transformation into material inputs for use in a different product or industry. Recently, there has been a lot of development in the arena of secondary material reclamation for PCC, and several emerging technologies are being explored in an attempt to introduce PCC as a material input to a variety of new industries. For this study, only two secondary product markets will be considered: carpet underlay and pelletized plastics, reinforced with glass fibers, for use in molding auto parts. The carpet underlay scenario recycles the face fibers, Nylon 6 and Nylon 6,6, into a needlepuched carpet padding, while the PCC backing materials are landfilled. The second scenario, transforms only Nylon 6,6 face fibers into the plastic pellets. The material and energy flows of these scenarios can be found in Figure 3.7 and Figure 3.8.

It is important to note that the SMR scenarios will be comparatively assessed a little differently. The first scenario involving the manufacturing of the carpet underlay will be compared not only against the baseline landfill scenario but also against the acquisition of the materials and the manufacturing of "virgin" carpet underlay. For the second case, involving the recycling of Nylon 6,6 face fibers into plasticized pellets, the EOL scenario will also be compared twice – once against the baseline landfill scenario and once against the manufacturing of virgin fiber reinforced nylon pellets. This second assessment, although not directly related to the carpet industry within which this study is being conducted, will provide "goodwill" insight into the overall environmental impacts of two separate industries working symbiotically to reduce waste and the utilization of virgin materials. However, the flow of the recycled second-use material out of the system boundaries also represents potential revenue for the carpet industry.

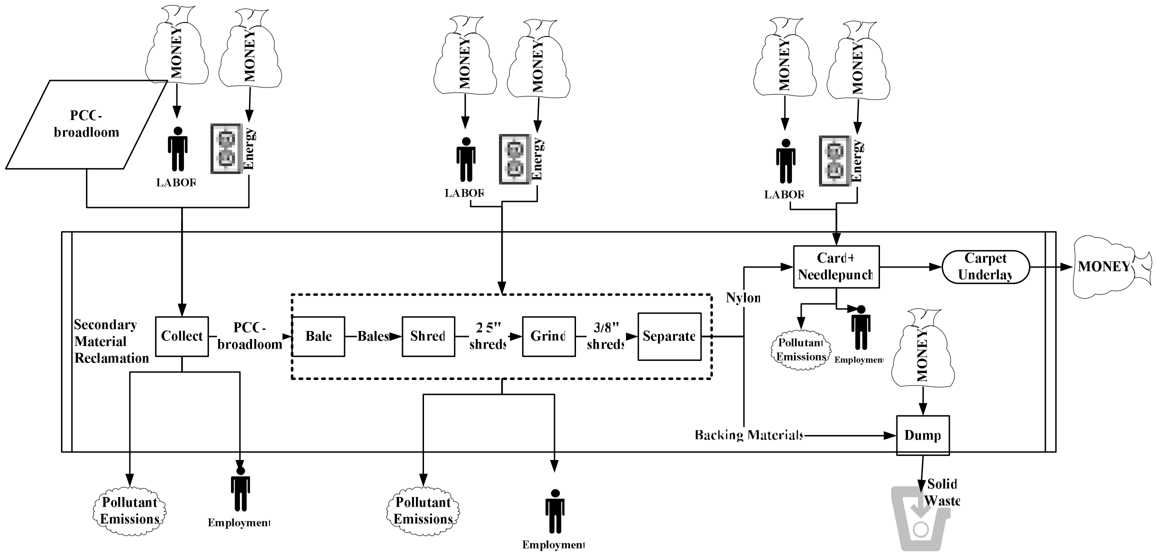


Figure 3.7: Secondary Material Reclamation - Carpet Underlay

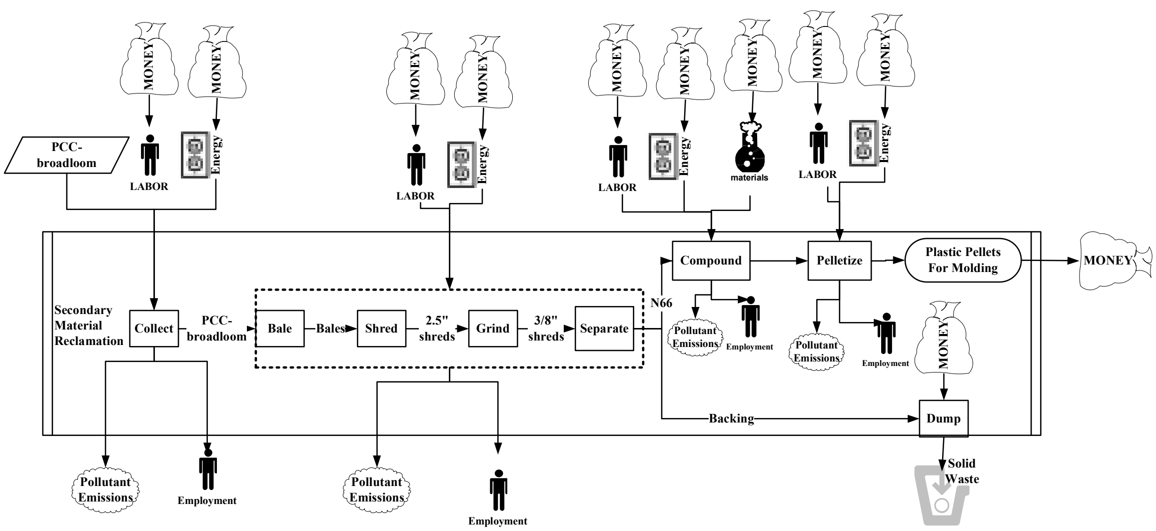


Figure 3.8: Secondary Material Reclamation – Pelletized Plastics for Molding

Based on the EOL scenario described above, and taking into account the Goal and Scope of the comparative LCA, the rest of this thesis contains several chapters dedicated to building a meaningful LCI database for the study. Once the LCI is complete, the information is translated into social, economic and environmental impact indicators, which are then assessed individually and against one another. Finally, recommendations for PCC waste management strategies are made based on the comparative assessments between the various EOL scenarios outlined above.

CHAPTER 4

LIFE CYCLE INVENTORY - ENERGY

4.1 Electricity

Electricity use can account for a rather large portion of the energy consumption and environmental impacts uncovered in a LCA. Generally, LCIs utilize pollution emission rates based on the weighted average of national power grid mixes to account for the effects of electricity consumption in the LCA. However, power mixes can vary a great deal from region to region; this could have significant effects in the local impacts studied in an LCA. Table 4.1 compares the current U.S. power generation mix against Georgia's mix (EIA, 2007). The rest of this chapter contains facts and pollution rates for Georgia based on nationally reported emissions statistics from local power plants throughout the state.

Table 4.1: National versus Georgia State Power Mix

Primary Fuel	% National Power Mix	% Georgia Power Mix
Coal	49.0%	65.5%
Natural Gas	20.0%	4.4%
Nuclear	19.4%	26.6%
Hydroelectric	7.0%	2.2%
Other Renewables	2.4%	1.3%
Petroleum	1.6%	0.0%
Other Gases	0.4%	0.0%
Other	0.3%	0.0%

4.1.1 Georgia Power Mix

The state of Georgia is home to ninety-nine power plants of varying capacities and fuel sources that collectively produce over 127 billion kWh of electricity annually. This mix of power plants is operated by fifty-one different operators, serves over eight different services areas and is owned by over seven parent companies. The primary fuels of these plants include coal, oil, gas, biomass, nuclear and hydraulic sources. The breakdown of the Georgia power grid by primary fuel type and percentage of overall energy output is found in Table 4.2 (eGRID, 2006).

Table 4.2: Georgia Power Mix

Primary Fuel	Fuel Type	Number Plants	% Total State Output
Bituminous Coal	coal	19	47.12%
Nuclear	nuclear	2	26.63%
Subbituminous Coal	coal	1	18.36%
Natural Gas	gas	23	4.37%
Water	hydraulic	30	2.22%
Black Liquor	biomass	5	1.23%
Wood (waste) Solids	biomass	2	0.03%
Residual Oil	oil	1	0.03%
Landfill Gas	gas	1	0.01%
Distillate Oil	oil	15	0.00%

The following sections of this chapter include descriptions of the various fuels used to supply electricity to the Georgia power grid. Additionally, the average emission rates for NO_x, SO_2, CO_2 and Hg pollutants based on the power plants in Georgia are characterized by grams-pollutant per kilowatt-hour produced [g-pollutant/kWh]. The chapter wraps up with an overall environmental and economic characterization of the power supply in Georgia delivered to local industrial markets.

4.1.2 Primary Fuels used in Georgia

The EPA characterizes a primary fuel, for the purposes of its eGRID database, as the fuel input with the greatest heat input for a given plant. The one exception is coal; if coal is consumed at all, regardless of its comparative heat input, it is considered the primary fuel. The following sections cover basic power generation and emission rates resulting from the primary fuels used in Georgia to generate power for the state (eGRID, 2006).

4.1.2.1 Coal Fuels

Two types of coal are burned in Georgia accounting for over 65% of the power supplied to the state electricity grid. Bituminous coal is burned at nineteen different plants to produce 47% of Georgia's power while subbituminous coal is burned at one plant located in Monroe County to produce approximately 18% of the power supply (eGRID, 2006). The spatial distribution of these plants within the state, depicted in Figure 4.1, is mapped using GoogleMaps.

Figure 4.1: Coal Plants in Georgia

The varieties of coal differ in energy and quality characteristics as a result of varying temperature, pressure and time spent in formation. Subbituminous coal is a lower rank coal. It has a higher moisture content, somewhere in the range of 20-30% by weight, and a lower energy content, due to its lower carbon content, averaging 17-18 million Btu per ton in the U.S. On the other hand, bituminous coal is a higher rank coal with an average moisture content of less than 20% and energy content around 24 million Btu per ton in the U.S. Because of the higher energy content, bituminous coal is the preferred fuel source, although it comes at a slightly higher economic cost as compared to subbituminous coal (EIA, 2008).

Over 90% of the coal-fired plants in the U.S. are run on pulverized coal combustion systems. In a pulverized coal combustion system, the coal is milled to a fine powder in order to increase surface area allowing for a quicker burn. The pulverized coal is blown into a combustion chamber where it is burned at high temperatures. The heat created from the burn adds energy to water creating a high power steam that begins to rotate turbine blades. The turbine blades lead to electricity generation from its rotation within a strong magnetic field. This electricity is then transformed to higher voltages and enters the power grid. Figure 4.2 contains an illustration of a pulverized coal combustion system (WCI, 2005).

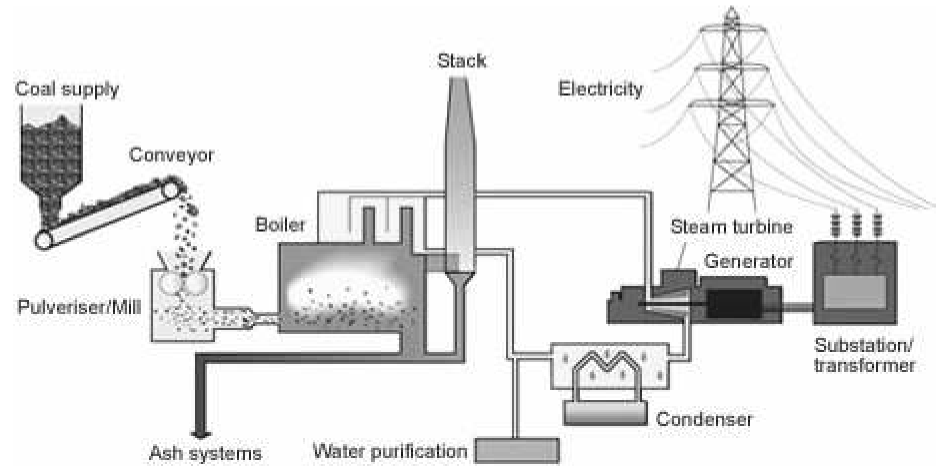


Figure 4.2: Pulverized Coal Combustion System (WCI, 2005)

In Georgia, these pulverized coal combustion systems contribute to nearly 65% of the power; however, the burning of the coal is also the cause for over 97% of NO_x emissions, 99% of SO_2 emissions, 96% of CO_2 emissions, and 100% of Hg emissions in the state. Table 4.3 contains the emissions rates, based on weighed averages of emission outputs reported by the coal plants in Georgia, for each of the pollutants emitted per kWh produced[4] (eGRID, 2006).

Table 4.3: Pollution Rates for Coal Facilities

Fuel	NO_x [g/kWh]	SO_2 [g/kWh]	CO_2 [g/kWh]	Hg [g/kWh]
Bituminous Coal	1.32	7.51	892.76	0.000014
Subbituminous Coal	0.71	3.11	997.96	0.000030

4.1.2.2 Nuclear Fuel

Nuclear power is the second largest power generation source in Georgia behind coal. It accounts for nearly 27% of the state's electricity and is produced at two plants (eGRID, 2006). The Edwin I. Hatch facility is located near Baxley in Appling County, and the Vogtle plant is located near Augusta in Richmond County. Nuclear power is generated by the heat released from the fission of uranium fuel in nuclear reactors. No

[4] All emission rates discussed are based on electricity generated on site and not on the electricity delivered for use, which would include losses associated with the distribution of the electricity.

pollutant emissions occur as a direct result of the fission; the only pollution is a result of the construction of the nuclear facility and the transportation of the fuels themselves. There is some nuclear waste resulting from spent fuels that is typically stored on site. However, in this study, the only pollution accounted for in the LCI is the air pollution resulting from direct electricity production. Thus, nuclear energy is considered a clean energy source with zero pollutants emitted (EPA, 2007).

4.1.2.3 Natural Gas

Natural gas is a nonrenewable energy source that can be burned in a boiler to produce steam, burned in a combustion turbine to produce electricity, or utilized in a combined cycle where the gas is burned in a combustion turbine and the heat from the exhaust is used to make steam which drives a turbine. Although still a fossil fuel, nationally natural gas emits about half as much CO_2, less than a third as much NO_x and only 1% of the total SO_2 emitted by coal-fired power generation (EPA, 2007). In Georgia, electricity produced from natural gas at facilities in Appling and Burke Counties accounts for almost 5% of the total energy stream and about 2% of NO_x and 4% of CO_2 emissions (EIA, 2008). The pollutant emission rates of the natural gas facilities in Georgia are found in Table 4.4 (eGRID, 2006).

Table 4.4: Pollution Rates for Natural Gas Facilities

Fuel	NO_x [g/kWh]	SO_2 [g/kWh]	CO_2 [g/kWh]	Hg [g/kWh]
Natural Gas	0.01	0.0004	24.84	0

4.1.2.4 Renewable Fuels

Renewable energy sources account for about 3.5% of Georgia's power; this includes landfill gas, biomass fuel (black liquor and solid wood waste), and hydraulic power. Landfill gas is used in small amounts to produce approximately 0.01% of Georgia's electricity from one facility located in Gwinnett County. Landfill gas is composed primarily of CH_4, CO_2 and VOCs and is a byproduct of naturally occurring organic waste decay. The burning of landfill gas does emit some pollutants, mainly NO_x and CO_2; however, the CO_2 emitted is considered part of the natural carbon cycle and thus is not counted as a pollutant for life cycle accounting purposes. Additionally, it is assumed that the landfill gas would normally be flared if not used to supply electricity, thus the SO_2 emissions from the electricity generation are offset by the emissions of a typical flare. Burning landfill gas also prevents CH_4 from being leaked into the atmosphere thus reducing another GHG emission rate (EPA, 2007). The pollutant emission rates of the landfill gas facility in Georgia are found in Table 4.5 (eGRID, 2006).

Black liquor and solid wood waste are both biomass renewable fuels. A biomass fuel is derived from organic matter, and for life cycle accounting purposes, is considered carbon neutral because its decomposition is part of the natural carbon cycle. Black liquor is a waste product of pulp and paper mills and is considered a biomass fuel source because it is derived from organic wood and paper materials. It is typically used to provide power for the pulp mill from which it came; however, in Georgia, there is a surplus and thus the plants in Liberty, Chatham, Macon, Wayne and Glynn Counties supply energy to the electricity grid accounting for a little over 1% of the total power produced in state. Solid wood waste, the other biomass fuel, accounts for approximately 0.03% of the total state's power and is burned at facilities in Glynn and Rabun Counties. The typical pollution rates of the biomass plants are located in Table 4.5 (eGRID, 2006).

The last renewable fuel used in Georgia, which contributes to slightly over 2% of the total power supply, is water. Although there is waste and pollution generated from the construction of the hydraulic power systems themselves, the actual generation of electricity emits no pollutant waste. Thus, the emissions from hydraulic power, included in Table 4.5, are zero for all the pollutants considered in this study (eGRID, 2006).

Table 4.5: Pollution Rates for Renewable Fuel Plants

Fuel	NO_x [g/kWh]	SO_2 [g/kWh]	CO_2 [g/kWh]	Hg [g/kWh]
Landfill Gas	0.0001	0	0	0
Black Liquor	0.007	0.019	0.48	0
Solid Wood Waste	0.0002	0.00003	0.01	0
Hydraulic Power	0	0	0	0

4.1.3 Georgia Power Statistics

4.1.3.1 Pollutant Emissions Statistics

Based on the percentage of total electricity generated by fuel type described in Table 4.2 and the average pollutant emissions rates for each fuel characterized in Section 4.1.2, a weighted average for pollutant emissions rates for electricity produced in Georgia is summarized in Table 4.6. The emission rates for Georgia are comparable to national averages. Although, per kWh, Georgia is averaging a 20% reduction in NO_x emissions, increases of 67% and 2% in SO_2 and CO_2 emissions respectively, and an equivalent Hg emission rate (eGRID, 2006). The rates located in Table 4.6 will be used to measure the environmental impacts of electricity consumption in this study.

Table 4.6: Annual Output Emission Rates for Georgia

NO_x [g/kWh]	SO_2 [g/kWh]	CO_2 [g/kWh]	Hg [g/kWh]
0.77	4.13	629.74	0.000012

4.1.3.2 Retail Price for Industrial Sector

The cost of electricity has been on the rise due in part to the increasing costs of fuels and the added costs associated with environmental improvements. Figure 4.2 is a graph of the average retail price of electricity supplied to the industrial sector in the U.S. between 1993 and 2007. There has been an overall average yearly increase of 2% with a total increase of 31% in the industrial retail price of electricity since 1993 (EIA, 2008).

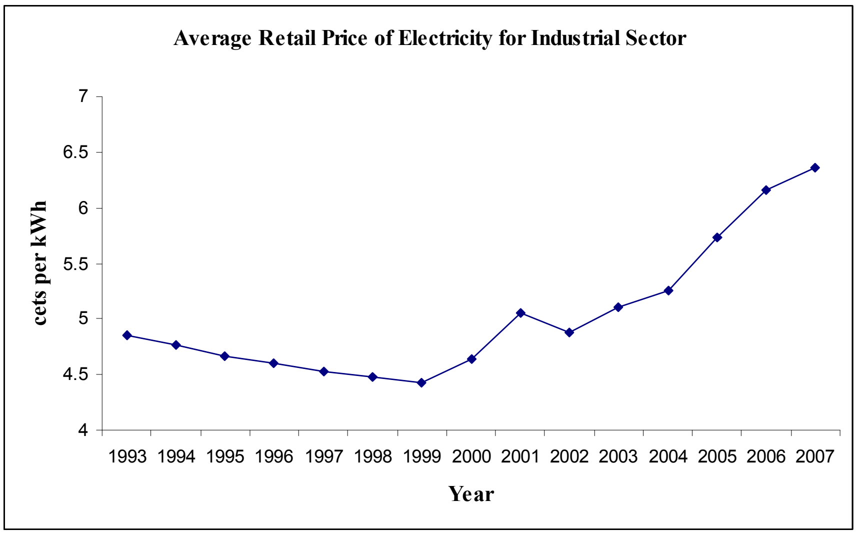


Figure 4.3: Average U.S. Retail Price of Electricity for Industrial Sector

The industrial retail price of electricity in Georgia is slightly below the national rate. The average price in 2006 was 5.38¢/kWh±1% and 5.48¢/kWh±1% in 2007. This shows a yearly increase of 2% between 2006 and 2007, which agrees with the national yearly increase rates (EIA, 2008). For this study, it will be assumed that the 2% increase in price will drive the retail price of electricity to the industrial sector in the state of Georgia to 5.59¢/kWh in 2008.

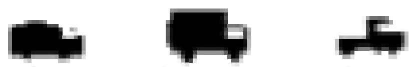
4.2 Transportation and Diesel Fuel

This section outlines the assumptions, inputs and outputs needed to complete the LCI for all transportation related activities. The data found in this section of the LCI will be used to determine the social, economic and environmental impacts of the transportation of goods throughout the various EOL scenarios. This includes the movement of PCC from collection sites to transfer stations and recycling facilities and the movement of materials from collection sites and recycling facilities to landfills. First the assumptions and characteristics of the vehicles and fuels considered will be discussed. This will be followed by an exploration of possible collection schemes in order to define the LCI for the collection process in general.

4.2.1 Assumptions on Transportation Vehicles

There are a variety of vehicles used in reverse logistics networks which vary according to the collection scheme and estimated product inventories. For the purposes of this study, several heavy duty diesel vehicles (HDDV) are considered ranging in class size from 2B to 8A (e.g., a van to a typical 18-wheel tractor-trailer). Table 4.7 contains information regarding the vehicles investigated in this study including their respective gross vehicle weight ranges (GVWR) and typical nomenclature defined by weight class (EPA, 2002).

Table 4.7: Vehicle Weight Classification

Illustration	GVWR [kg]		Weight Class
	3856	4536	HDDV-2B
	4536	6350	HDDV-3
	6351	7257	HDDV-4
	7258	8845	HDDV-5
	8846	11793	HDDV-6
	11794	14969	HDDV-7
	14969	27216	HDDV-8A

Since this comparative LCA EOL study is being conducted in 2008, the transportation model is based on estimates, performance specifications and EPA pollutant emissions regulations for HDDVs with model years between 2000 and 2003. The EPA has determined the useful life of HDDVs to be approximately eight years for vehicles with model years between 1998 and 2003 (DieselNet, 2007). Thus, the oldest probable HDDVs comprising fleets today are from 2000. Generally, HDDVs are retired at their projected life expectancy, thus it is likely that the vehicles en route today are older models. Additionally, limiting HDDVs studied to models between 2000 and 2003, allows for a direct correlation to the first tier of EPA HDDV emissions' regulations.

The pollutant emissions rates resulting from the use of diesel fuel in the transportation portions of the EOL scenarios are determined by both regulations enacted and estimates made by the EPA and theoretical complete combustion formulas for diesel. In Table 4.8 the source of each emission rate for all of the environmental impact categories considered in the study have been identified.

Table 4.8: Source of Emissions Calculations

Pollutant		Source of Emission Statistic
Greenhouse Gases	CO_2	chemical combustion formula: based on fuel carbon content and density
	CH_4	estimated (not regulated) by EPA
	N_2O	estimated (not regulated) by EPA
Criteria Pollutants	SO_2	chemical combustion formula: based on regulated fuel sulfur content and density
	NO_x	regulated by EPA
	Pb	not reported
	CO	regulated by EPA
Additional Pollutants	VOCs	not reported
	Hg	not reported
	HC	regulated by EPA
	PM	regulated by EPA
	SO_x	(assume SO is further oxidized in atmosphere; thus, included in SO_2 calculations)

The remainder of this section will focus on HDDV use and diesel fuel characteristics needed in order to estimate the pollutants emitted per mile traveled during the transportation phases of the EOL scenarios studied.

4.2.2 Energy Consumption Characteristics

Energy consumption in the transportation legs of the EOL scenarios are based on estimated average fuel economies (FE). FE is generally dependent on vehicle loads, time spent idling, road characteristics (e.g., highway or city) and engine efficiencies. The EPA has published models used to estimate the FEs of all ranges of HDDVs for their MOBILE6 Vehicle Emission Modeling Software. The FE equations are based on data collected for vehicles with model years between 1993 and 1996. The equation below, where FE is fuel economy and MY is model year, was used to determine the FEs for the HDDVs based on the regression coefficients found in

Table 4.9 (EPA, 2002).

$$\ln(FE) = A + B \cdot \ln(MY - 1900) \qquad \textbf{Equation 1}$$

Table 4.9: Fuel Economy Equation Coefficients

HDDV	A	B
HDDV-2B	0.1072	1.0506
HDDV-3	0.0989	1.0450
HDDV-4	0.5020	0.6598
HDDV-5	0.2474	0.8078
HDDV-6	0.5336	0.6117
HDDV-7	4.0206	0.1374
HDDV-8A	0.15485	0.8194

The average fuel economies for all weight classes of HDDVs with model years between 2000 and 2003 have been extrapolated based on the equation above; the results are located in Table 4.10.

Table 4.10: Fuel Economies for HDDVs Model Year 2000-2003

HDDV-	FE [mpg]
2B	13.7
3	12.4
4	10.6
5	10.3
6	9.0
7	7.6
8A	6.8

In addition to the traditional fuel economy of the vehicles, it is also necessary to estimate the average speeds at which the vehicles will be traveling. This study assumes an average of 55mph for all vehicles in every transportation related activity and scenario. This estimate is based on the regulated maximum highway speed limit for urban areas which was set at 55mph back in 1974. Even though Georgia took advantages of the lift of this federal regulation back in 1996 by raising the maximum speed limit on urban interstates to 65mph, it is still likely that the HDDV themselves, on average, are traveling at slightly slower speeds. Additionally, considering the city street driving speeds of the transportation process the overall average speed will drop due to idling tendencies and lower limits. Lastly, according to EPA funded studies, pollution emissions generally rise as speeds increase over 48mph (E.H. Pechan & Associates, 1995). Therefore, given these considerations, all speeds evaluated as 55mph.

4.2.3 Characteristics of Diesel Fuel

As part of the EPA's Clean Air Highway Diesel Rule, ultra low sulfur diesel (ULSD) fuel is required at the pump as of summer 2006. The regulation requires that the sulfur content of diesel fuel be reduced by nearly 97% from a 1990 mandated maximum of 500ppm for low sulfur diesel (LSD) fuel. The actual US average of the early 1990s was around 340ppm. This current ruling caps the sulfur content of ULSD at 15ppm. Currently, retailers are still allowed to sell the LSD fuel to HDDVs with a pre-2007 model year. However, for the purposes of this study, only the use of ULSD consumption in the transportation portion of the EOL LCA will be considered. This choice will greatly reduce the environmental impact of transportation on the EOL system as compared to the use of LSD fuel; however, there will be around a 1% increase in the economic impact due to the higher costs of ULSD (EIA, 2008).

Two of the unregulated pollutant emissions considered in this study, CO_2 and SO_2, are estimated by the chemical equations for the complete combustion of diesel fuel (Govetto, 2007). The chemical formula labeled Equation 2 captures the combustion of diesel, where $n = 12$ and $k = 16$ in accordance to the chemical formula for diesel, $C_{12}H_{16}$.

Equation 2

$$C_nH_k\left(\frac{k}{4}+n\right)(O_2+3.76N_2)+S \Rightarrow nCO_2+\left(\frac{k}{2}\right)H_2O+3.76\left(\frac{k}{4}+n\right)N_2+SO_2$$

It is assumed that all carbon is converted to CO_2 during the combustion; therefore, this method will provide an upper estimate of the mass of CO_2 emitted per mile, which can be calculated using Equation 3. Additionally, it is assumed that a full oxidation of the sulfur occurs in the combustion. Thus, any SO that may result from the combustion in reality, is here captured in total SO_2 emitted. Again, this method provides an upper estimate for grams of SO_2 emitted per mile, which is determined by Equation 4 (Backstrom, 2005). Although the diesel combustion equation is generic, the CO_2 and SO_2 pollutants emitted rely on the actual physical properties of the diesel fuel being used. The fuel density (FD), carbon content (CC) and sulfur content (SC) can be found in Table 4.11 (NREL, 2007). Assuming the FEs listed in Table 4.10, as discussed in Section 4.2.2, the CO_2 and SO_2 pollutant emissions emitted per mile traveled are found in Table 4.12.

Table 4.11: Diesel Fuel Properties

Fuel Type	FD [kg/gal]	CC [%-wt.]	SC [ppm-wt.]
ULSD	3.1	85.5%	19.6

$$CO_2\left[{}^{kg}\!/_{gal}\right] = \left(\frac{44}{12}\right) CC \cdot FD \qquad \textbf{Equation 3}$$

$$SO_2[kg/gal] = (2) SC \cdot FD \qquad \textbf{Equation 4}$$

Table 4.12: Calculated Theoretical Pollutant Emissions

HDDV-	CO_2 [g/mile]	SO_2 [g/mile]
2B	704	0.009
3	783	0.010
4	915	0.011
5	937	0.012
6	1075	0.013
7	1276	0.016
8A	1419	0.018

4.2.4 EPA Regulated and Estimated Emissions Statistics

For the regulated emissions, the EPA has set up a tiered system based on truck model year for all diesel commercial-use trucks. All emissions are reported as grams-pollutant emitted per brake-horsepower•hour [g-pollutant/bhp•hr]. The regulations based on vehicle model year are outlined in Table 4.13 (DieselNet, 2007).

Table 4.13: EPA Emissions Commercial Diesel Engine Emissions Regulations

Model Year	HC[5] [g/bhp·hr]	CO [g/bhp·hr]	NO_x [g/bhp·hr]	PM [g/bhp·hr]
1998-2003	1.30	15.50	4.00	0.10
2004-2006	0.50	15.50	2.00[6]	0.10
2007 +	0.14	15.50	0.20	0.01

Although there are a variety of ways to achieve the emissions standards set by the EPA and outlined in Table 4.13, the study will not explore the individual technologies available. It will only assume that at least the minimum regulations are met for the entire HDDV fleet considered.

The EPA has chosen to regulate emissions based on [g-pollutant/bhp•hr]; this, however, does not conform to the functional units chosen in this study for transportation related pollutant emissions. Thus, it is necessary to convert [g-pollutant/bhp•hr] to grams of pollutant per mile [g-pollutant/mile]. The necessary conversion factor (CF) is based on FD, brake-specific fuel economy (BSFC) and FE and follows the format of Equation 5 (EPA, 2002).

$$\text{Conversion Factor} = \frac{FD}{BSFC \cdot FE} \qquad \textbf{Equation 5}$$

[5] HC here refers to non-methane hydro carbons or NMHC; CH_4 emissions remain unregulated by the EPA.
[6] There are two levels of regulations for vehicles with Model Years 2004-2006. Option one regulates the sum of HC and NO_x pollutants with a cap of 2.4 g/bhp-hr. Option two caps the sum of HC and NO_x pollutants at 2.5 g/bhp-hr and capping the HC pollutants at 0.5 g/bhp-hr. The numbers shown in Table 4.13 capture the regulations of the second option.

The average FD of ULSD fuel is approximately 3.1 kg/gallon (0.82 kg/L) (Table 4.11) (NREL, 2007). The average FE estimates of HDDVs are found in Table 4.10. The BSFCs for the HDDVs are calculated using a logarithmic curve that was extrapolated from sales-weighted manufacturer engine specifications for model years 1987 to 1996. The resulting BSFCs found in Table 4.14 are an average based on the current expected fleet according to model years 2000 to 2003. The CFs are then calculated according to Equation 5 (EPA, 2002).

Table 4.14: Brake-Specific Fuel Economies and Conversion Factors

HDDV-	BSFC	CF
2B	0.466	1.1
3	0.448	1.2
4	0.464	1.4
5	0.454	1.5
6	0.407	1.9
7	0.385	2.3
8A	0.381	2.6

Using the CFs calculated in Table 4.14, the EPA regulated emissions are converted into a [g-pollutant/mile] format for each category of HDDV. Again, only HDDVs with model years 2000 to 2003 are being considered due to an expected vehicle life of eight years, thus Table 4.15 contains the regulated pollutant emission rates for the first tier of EPA regulations in units of [g-pollutant/mile].

Table 4.15: HDDV Regulated Emissions

HDDV-	HC [g/mi]	CO [g/mi]	NO_x [g/mi]	PM [g/mi]
2B	1.37	16.33	4.22	0.11
3	1.58	18.85	4.86	0.12
4	1.81	21.56	5.57	0.14
5	1.91	22.71	5.86	0.15
6	2.42	28.89	4.76	0.19
7	3.05	36.40	9.39	0.23
8A	3.42	40.80	10.53	0.26

Although the EPA has not regulated CH_4 and N_2O emissions, they have developed a methodology, based on the *Revised 1996 Intergovernmental Panel on*

Climate Change Guidelines, for estimating the emissions. The revised methodology takes into consideration average industry estimates for HDDV-use based on vehicle type, FE and vehicle miles traveled. The development of the EPA's estimates is documented in Annex 3 of the Inventory *of U.S. Greenhouse Gases Emissions and Sinks: 1996-2004* report (EPA, 2006). The resulting CH_4 and N_2O emissions estimates for HDDVs with advance controls, defined as HDDVs with a model year between 1996 and 2004, can be found Table 4.16 .

Table 4.16: Estimated CH_4 and N_2O Emissions Rates

HDDVs	**CH_4 [g/mi]**	**N_2O [g/mi]**
Model Year 1996-2004	0.005	0.005

A summary of all pollution emission rates for HDDVs is found in Table 4.17.

Table 4.17: Summary of Pollutant Emissions Rates for HDDVs

	Greenhouse Gases [g-pollutant/mile]			**Criteria Pollutants** [g-pollutant/mile]				**Additional Pollutants** [g-pollutant/mile]				
HDDV-	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
2B	704	0.005	0.005	0.009	4.22	N/R	16.33	N/R	N/R	1.37	0.11	N/R
3	783	0.005	0.005	0.010	4.86	N/R	18.85	N/R	N/R	1.58	0.12	N/R
4	915	0.005	0.005	0.011	5.57	N/R	21.56	N/R	N/R	1.81	0.14	N/R
5	937	0.005	0.005	0.012	5.86	N/R	22.71	N/R	N/R	1.91	0.15	N/R
6	1075	0.005	0.005	0.013	4.76	N/R	28.89	N/R	N/R	2.42	0.19	N/R
7	1276	0.005	0.005	0.016	9.39	N/R	36.40	N/R	N/R	3.05	0.23	N/R
8A	1419	0.005	0.005	0.018	10.53	N/R	40.80	N/R	N/R	3.42	0.26	N/R

4.2.5 Transportation Economics and Labor Requirements

This section includes the assumptions leading to and the definitions of the social and economic inputs and outputs needed to complete the LCI for the transportation processes.

4.2.5.1 Cost of Fuel

Fuel costs are on the rise. In the past year, the national retail highway price for ULSD has risen over 45%. More locally, in the Lower Atlanta regions, including Virginia, West Virginia, North Carolina, South Carolina, Georgia and Florida, the retail price has jumped over 47% from March 2007 to March 2008. Monthly, the trend in the Lower Atlantic region for ULSD is an increase of 3.75%. As mentioned in Section 4.2.3, Only the use of ULSD which has greater environmental benefits than LSD but a slightly higher economic impact of nearly 1% per gallon will be considered. However, the retail price trends of all highway diesels are relatively similar as the graph in Figure 4.4 supports. As a baseline estimate for the economic impacts associated with the cost of diesel fuels, the monthly average retail price of \$3.876 per gallon (\$1.024/L) in March 2008 for ULSD in the Lower Atlantic Region will be used in this study (EIA, 2008).

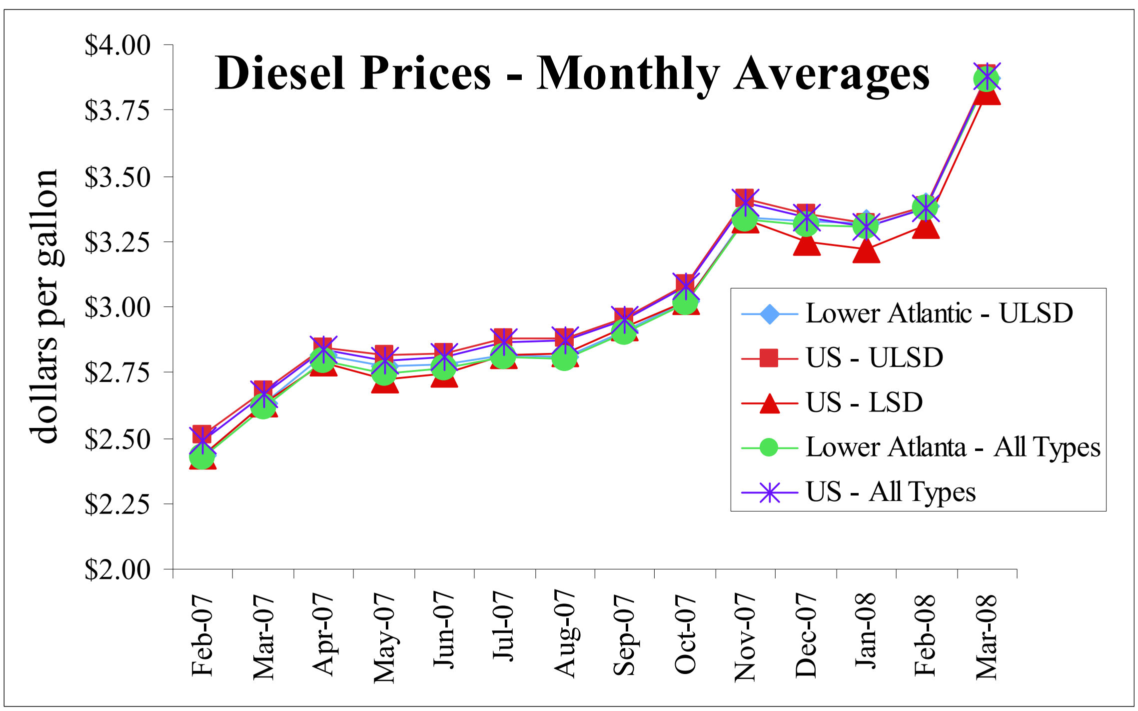


Figure 4.4: Monthly Retail Prices for Highway Diesels

4.2.5.2 Cost of Labor

According to the US Bureau of Labor Statistics (BLS), the Transportation and Material Moving Occupations are sub-divided into thirty-eight different categories. The most pertinent category for use in this study is the Refuse and Recyclable Material Collectors, which is defined as the collecting and dumping of recyclable materials from containers into trucks, including the actual truck driving as well. The average compensation for employees in this category is available at the metropolitan, state and national levels for the year 2006. More recent surveys, however, do not include this particular sub-category for Transportation and Material Moving Occupations. However, there are two other sub-categories that could also be used as a reference for this study that do have compensation data for 2006 and 2007. These categories are defined according to vehicles driven: Truck Drivers, Heavy and Tractor-Trailer and Truck Drivers, Light or Delivery Services. Truck Drivers, Heavy and Tractor-Trailer occupation is described as truck driving with a GVW greater than 11793kg in order to transport and deliver goods; drivers may also be required to unload trucks. The Truck Drivers, Light or Delivery Services occupation is described as driving a truck or van with a GVW of less than 11793kg and includes delivery and pick-up of goods within a specified area; drivers may also be required to load and unload trucks (BLS, 2007). Unfortunately, the BLS data is not updated in any of the Transportation and Material Moving Occupations categories for national or state aggregated data for 2007; however, there are wage rates published at the metropolitan level for 2007.

A comparison of the hourly wages, based on 2006 averages at the metropolitan, state and national data for all of the pertinent Transportation and Material Moving

Occupations categories discussed above can be found in Figure 4.5 (BLS, 2007). Figure 4.6 contains a graph of some historical compensation data from 2005 to 2007 for the Transportation and Material Moving Occupations and aggregated Truck Driver categories at the Atlanta metropolitan region (BLS, 2007). The error bars represent the relative error for each data set as reported by the BLS.

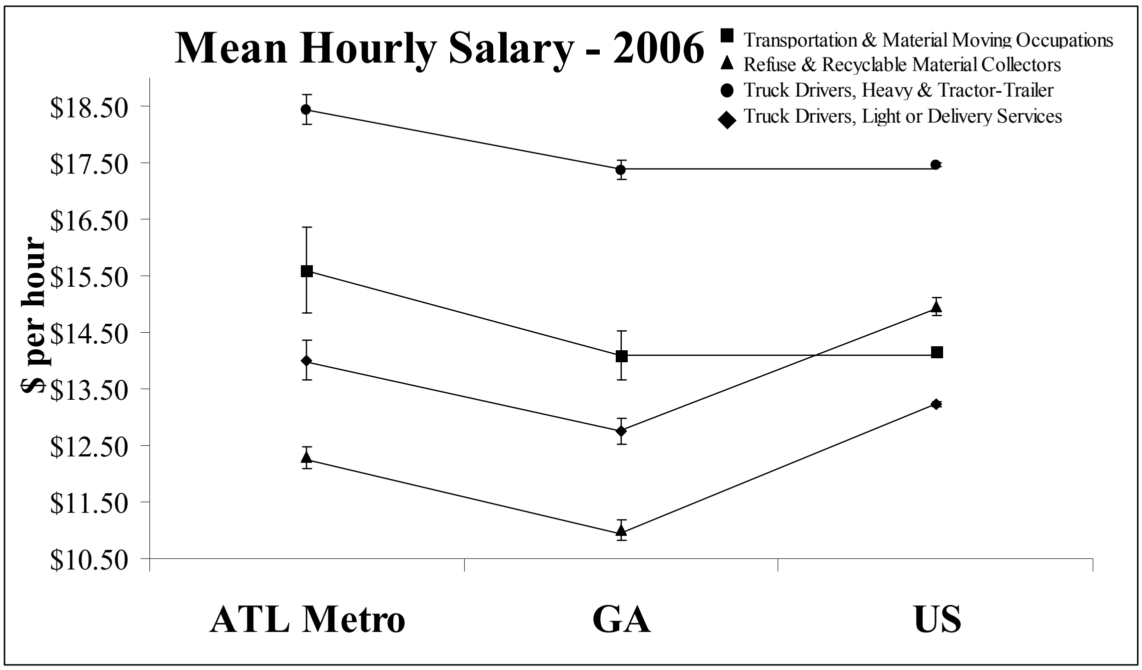


Figure 4.5: Mean Hourly Wage Rates by Occupational Category & Geographic Region – 2006

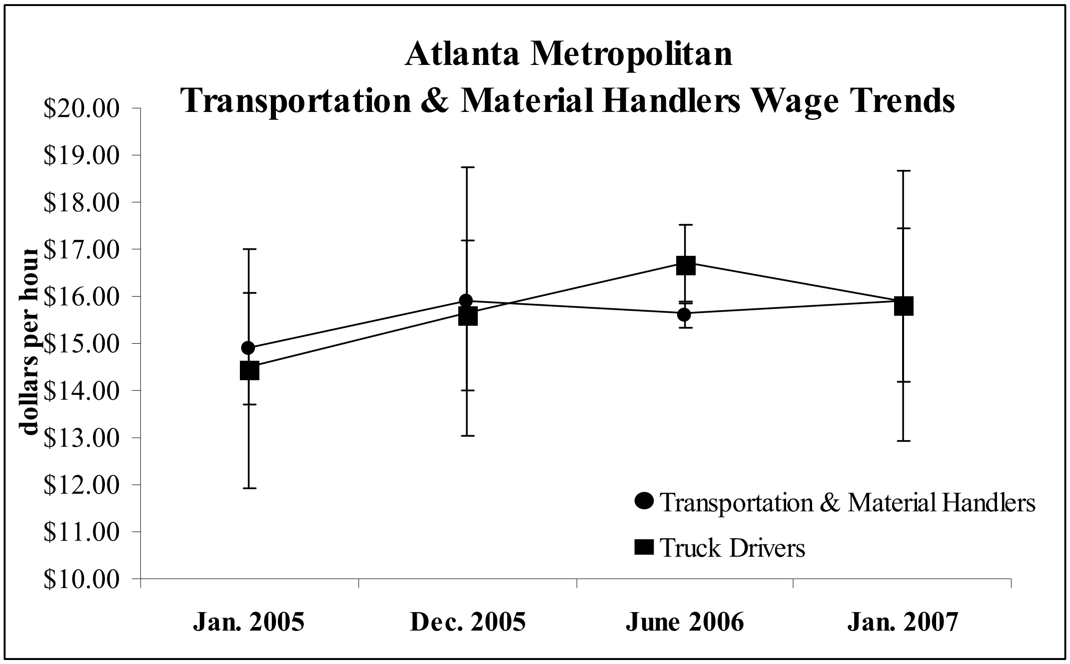


Figure 4.6: Atlanta Metropolitan Hourly Wage Rates

As suggested by Figure 4.5, it appears that the Georgia state averages are less than the national averages while the Atlanta Metropolitan Region is generally slightly higher than the overall state averages. The Truck Drivers: Heavy and Tractor-Trailer is by far the highest paying category. It is shocking to note that on average the Refuse and Recyclable Material Collectors are averaging wage rates nearly 22% lower in Georgia (at the state and metropolitan levels) than the average Transportation and Material Handlers Occupations general classification; nationally it is an average pay decrease of 6%. Figure 4.6 shows a relatively slight increase in hourly wages over the past two years for the overall Transportation and Material Handlers Occupations category and for the aggregated (employee based weighted averages of average hourly wage rates) Truck Drivers category. At the metropolitan level, there is an average pay difference between the two categories of 4.2% with the Truck Drivers hourly salary generally less than the overall Truck and Material Handlers Occupations category. There is a generalized trend of a 2% and 4% wage increase per month for the Transportation and Material Handlers Occupations category and Truck Drivers category respectively. For the purpose of this study, the aggregated Truck Drivers wage trends, which most accurately represented the job description of the employees performing the transportation operations of each scenario, will be used. Thus, using the latest wage estimate of $15.82 per hour and applying a 4% increase per month, the hourly wage rate for Truck Drivers in 2008 will be estimated at $16.60, which includes the actual driving and loading and unloading of products.

CHAPTER 5

LIFE CYCLE INVENTORY – PRODUCT INVENTORY ESTIMATES AND COLLECTION

This chapter builds the LCI necessary to determine the amount of material available for collection annually. Additionally, a variety of collection schemes are explored in order to effectively represent the reverse logistics of the EOL scenario and to determine an appropriate method for estimated the impacts of such schemes.

5.1 Product Inventory Estimates

5.1.1 Methodology

In order to more accurately estimate the impacts and effects of EOL options for post-consumer products in an urban area, it is important to first understand the general quantity of material that is available for urban mining. Nancey Green Leigh, et. al from the City and Regional Planning group in the School of Architecture at The Georgia Institute of Technology have been developing a methodology for capturing the annual carpet stock up for disposal based on building structure use type, building square footage, and carpet lifespan. The general methodology is outlined in Figure 5.1 (Ai, 2007).

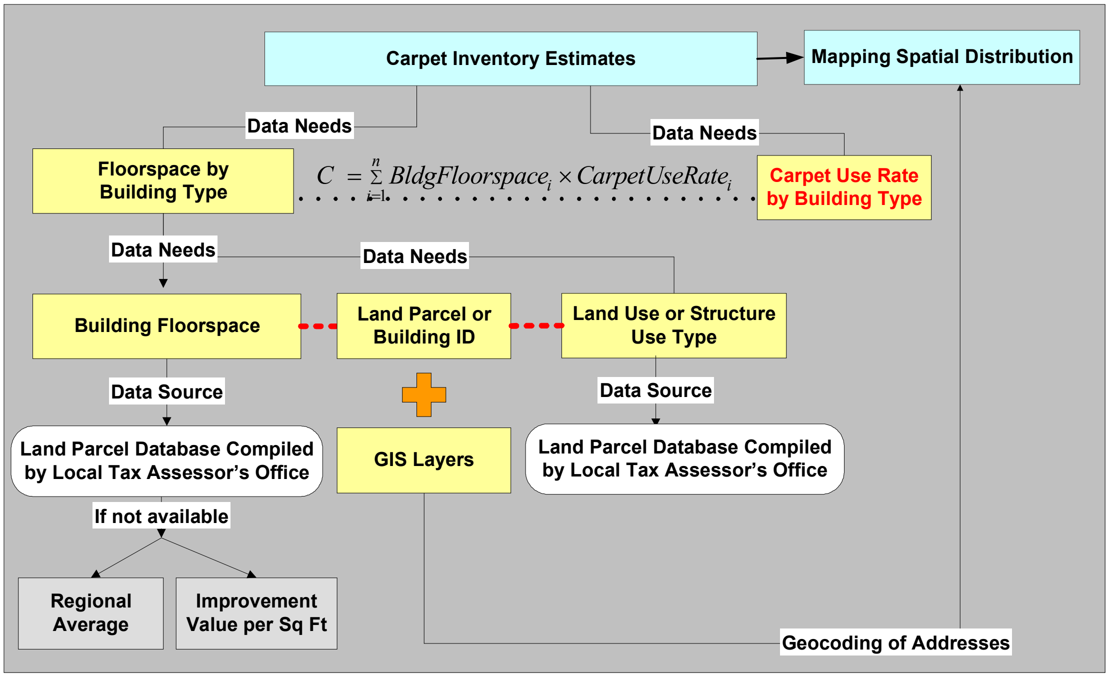


Figure 5.1: Methodology Developed for Carpet Inventory Estimates

This methodology utilizes publicly available data provided by the Local Tax Assessor's Office for building statistics and general carpet industry statistics available through such institutions as the Carpet and Rug Institute.

For the PIEs, thirteen SMARTRAQ data land use types found in the 13-county Atlanta metropolitan region, are first re-categorized into seven different carpet-use types. The transformation is detailed in Table 5.1.

Table 5.1: Atlanta Land Use Categories (Ai, 2007)

Land Use Categories by CGIS	Definition	Re-Categorization for Carpet Estimation
Agriculture	Property actively used in agriculture	NA
Cemetery/Park/Open Space	Public parks, cemeteries and open spaces	NA
Commercial	Wholesale and retail trade	Commercial
Industry	Manufacturing, light industry and warehousing	Industrial
Institutional	Government or other institutional uses	Institutional
Mobile Home	Single mobile home or mobile home park	Single-family
Multi-Family Residential	Apartment or other attached housing units	Multi-family
Office	High and low-rise offices	Office
Parking/TCU	Parking lot, structure or utility	NA
Recreation	Golf course or other recreation area	NA
Single-Family Residential	Owner occupied, detached housing unit	Single-family
Unknown	Use could not be determined	NA
Vacant	Undeveloped parcel	NA

Each of the seven designated carpet-use categories corresponds to an estimation of carpet per building by a percentage of overall floor space. The floor space percentages by building use type are found Table 5.2.

Table 5.2: Initial Estimates of Carpet-Use Rate (Ai, 2007)

Categorization for Carpet Estimate	Estimate Carpe use [% Floor Space]
Commercial	50%
Industrial	10%
Institutional	40%
Multi-family	90%
NA	0%
Office	90%
Single-family	80%

Using the carpet use categories detailed in Table 5.1 and their corresponding use rates found in Table 5.2, carpet inventory estimates for the Atlanta metropolitan region can be determined based on total estimated building square footage in the region. The PIEs are located in Table 5.3.

Table 5.3: Atlanta Carpet Inventory Estimates (Ai, 2007)

Categorization for Carpet Estimate	Building Sq. Footage	Estimated Carpet Use		Estimated Carpet Weight	
		[ft^2]	[m^2]	[lbs]	[kg]
Commercial	350,214,947	175,107,474	16,268,017	97,281,930	44,126,341
Industrial	371,800,262	37,180,026	3,454,137	20,644,570	9,364,219
Institutional	55,646,703	22,258,681	2,067,899	12,365,934	5,609,093
Multi-family	244,719,463	220,247,517	20,461,664	122,359,732	55,501,441
NA	257,262,017	0	0	0	0
Office	161,434,552	145,291,097	13,497,985	80,717,276	36,612,740
Single-family	2,263,418,807	1,810,735,046	168,222,790	1,005,963,914	456,297,556
TOTAL	3,704,496,751	2,410,819,840	223,972,492	1,339,344,356	607,516,381

The carpet estimates by weight are based on the industry statistics for broadloom and carpet-tiles. It is estimated that broadloom carpet accounts for 90% of the market while carpet-tiles compromise the remaining 10%. Additionally, it is assumed that broadloom weighs on average 4.5 lb/yd^2 (2.4 kg/m^2) and carpet tiles averages 9 lb/yd^2 (5 kg/m^2). A uniform average of carpet weight of 5 lb/yd^2 (2.7 kg/m^2) was used to calculate the inventory estimates of carpet by weight (Ai, 2007).

Using two different carpet lifespan estimates of ten and fifteen years, an annual estimate of available carpet for urban mining can be determined. With a total estimated carpet stock in the Atlanta metropolitan region of 607,516,381 kg, the predicted discarded carpet each year ranges from 60,751,638 – 40,501,092 kg. With an average population of around 4million people in the Atlanta metropolitan regions, this amounts to 10 – 14 kg-PCC disposed per person per year. A map of the spatially distributed PIEs for PCC in the 13-county Atlanta metropolitan region can be found in Figure 5.2 (Ai, 2007).

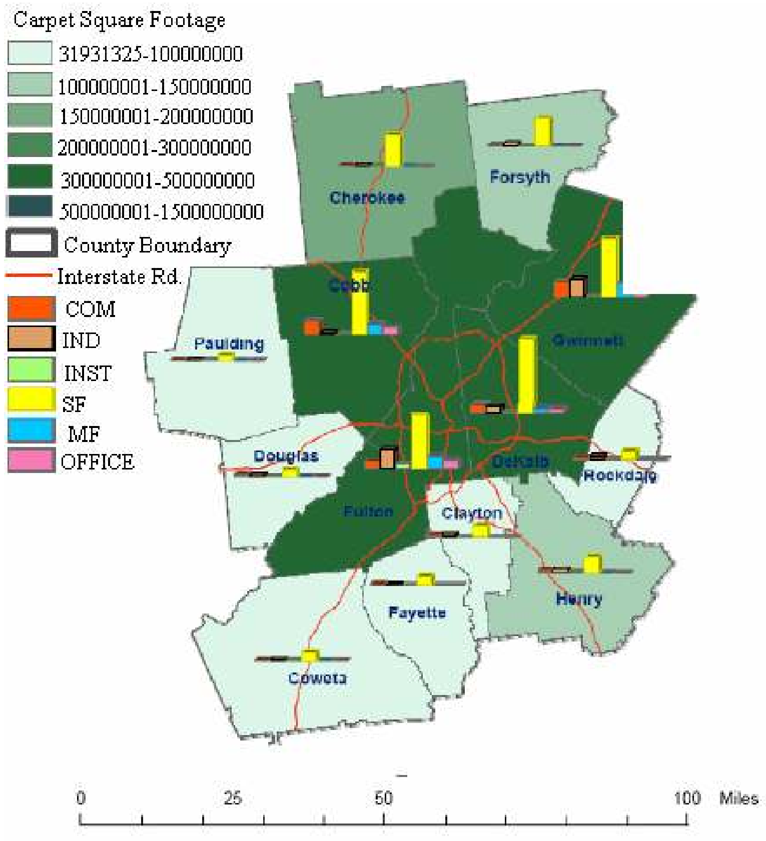


Figure 5.2: Spatial Illustration by County for Atlanta, Georgia (Ai, 2007)

5.1.1 Post-Consumer Carpet Inventory Estimates

Using the methodology for estimating available carpet stock for urban mining outlined in Section 5.1.1, a more spatially refined PIE can be found based on population estimates for the 13-counties and for the 142 zip codes of the Atlanta metropolitan region. The PIEs by county are found in Table 5.4. Refer to Appendix A.1 for PCC PIEs by zip code.

Table 5.4: Product Inventory Estimates by County

County	Population	Carpet Estimate [kg]	
		[10 kg/person/year]	[14 kg/person/year]
Cherokee	141,903	1,351,688	1,995,350
Clayton	236,517	2,252,928	3,325,752
Cobb	607,751	5,789,096	8,545,808
Coweta	89,215	849,812	1,254,485
DeKalb	665,865	6,342,657	9,362,970
Douglass	92,174	877,998	1,296,092
Fayette	91,236	869,320	1,283,282
Forsyth	98,407	937,370	1,383,737
Fulton	816,006	7,772,816	11,474,157
Gwinnett	588,448	5,605,226	8,247,381
Henry	119,341	1,136,776	1,678,097
Paulding	81,678	778,019	1,148,504
Rockdale	70,111	667,838	985,856
TOTAL	**3,698,679**	**35,231,544**	**52,008,470**

5.1.2 Material Inventory Estimates

Further refinement of the PIEs is necessary in order to determine the quantities of specific materials available for reclamation each year in the Atlanta region. Based on the PCC PIEs in Section 5.1.1 and carpet industry statistics described in Sections 2.2, Table 5.5 contains annual PIEs for the various PC materials that appear in this study.

Table 5.5: Annual Product Inventory Estimates by Material

Material	Annual Product Inventory Estimates [kg]		
	Lower Bound [10 kg/person/yr]	Average [10 kg/person/yr]	Upper Bound [14 kg/person/yr]
PCC-Broadloom	33,288,111	39,945,733	46,603,355
PCC-Tile	3,698,679	4,438,415	5,178,151
Nylon 6	6,125,012	7,350,015	8,575,017
Nylon 6,6	9,187,519	11,025,022	12,862,526
PVC	1,109,604	1,331,524	1,553,445

5.2 Collection Strategies

The various collection strategies involved in a reverse logistics network determine the type of vehicles used, and consequently the fuel type and consumption rates, and the mileage traveled. In order to encourage collection of PC goods, it is important that the collection strategy employed be convenient to the consumer; however, it must also be economical for the recycler while keeping in mind the overall EOL environmental impacts. The costs are determined by such factors as fleet size and truck capacity, storage space, mileage traveled, and collection schedules; and the environmental impacts of the collection scheme are a direct result of truck type, truck size and total mileage traveled. Therefore, it is necessary to minimize costs for the recycler while maximizing convenience for the consumer and minimizing the overall environmental impact of the EOL scenario. This multi-faceted objective will be used to explore various collection schemes in order to determine the preferable collection strategies for PCC collection within the Atlanta Metropolitan Region.

There are several overarching collection options that will be explored in this section. They are broken into two major categories: PCC-tile collection and PCC-broadloom collection. These categories are distinct in that their probabilistic locations are different. PCC-tile is primarily a commercial carpet, and thus is most likely concentrated in business districts. On the other hand, PCC-broadloom is primarily a residential market carpet, and thus its location is likely to be more geographically dispersed throughout the urban region. Additionally, PCC-tile is currently only recycled at Interface’s facilities in LaGrange, GA while PCC-broadloom carpet could potentially be recycled at facilities in both Calhoun and Dalton, GA. Based on these assumptions, the following diagram depicts the major collection scheme options that will be explored.

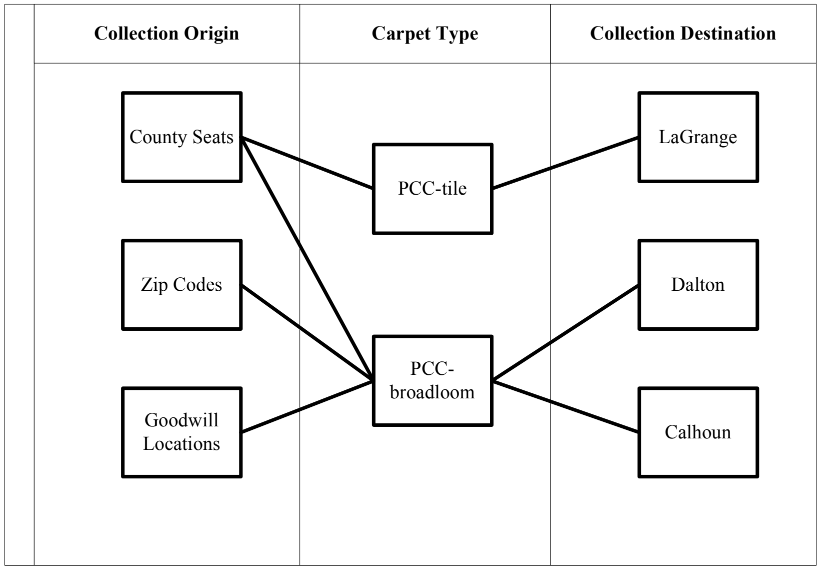


Figure 5.3: Collection Schemes

5.2.1 Post Consumer Carpet Tile Collection

In this section, the various collection schemes appropriate for PCC-tiles, which are highly concentrated in business and office settings are discussed. The first scenario explores the implications of collection schemes estimated from county seats to a recycling facility in LaGrange, GA while the second scenario explores the assumptions and strategies behind a geographically dispersed collection sites used to aggregate the PCC-tile before shipping it to LaGrange.

5.2.1.1 Post Consumer Carpet Tile Collection – County Seats

For the most generic PCC-tile collection case, it is assumed that all commercial PCC is PCC-tile and that it is concentrated in the county seats of each respective county. County seats are typically the most geographically concentrated business districts; thus, it is probable that the majority of available PCC-tile for reclamation would be located in these cities. Additionally, with the exception of Fulton County, the county seats have a relatively central geographic location within each county. Refer to Figure 5.4 for a visual of the Georgia counties and the county seats in the Atlanta Metropolitan Region.

The distances traveled for this collection are estimated by Google Maps and are based on the distance between the existing PCC-tile recycling facility in LaGrange, GA and the respective county seats in each of the thirteen counties. The overall distance traveled is thus a sum of the product of the number of trips, based on truck capacity and percent of truckload, and PCC-tile product estimates and the distance between the recycling facility and each county seat. Table 5.6 contains a list of the distances between the recycling facility and each of the thirteen county seats.

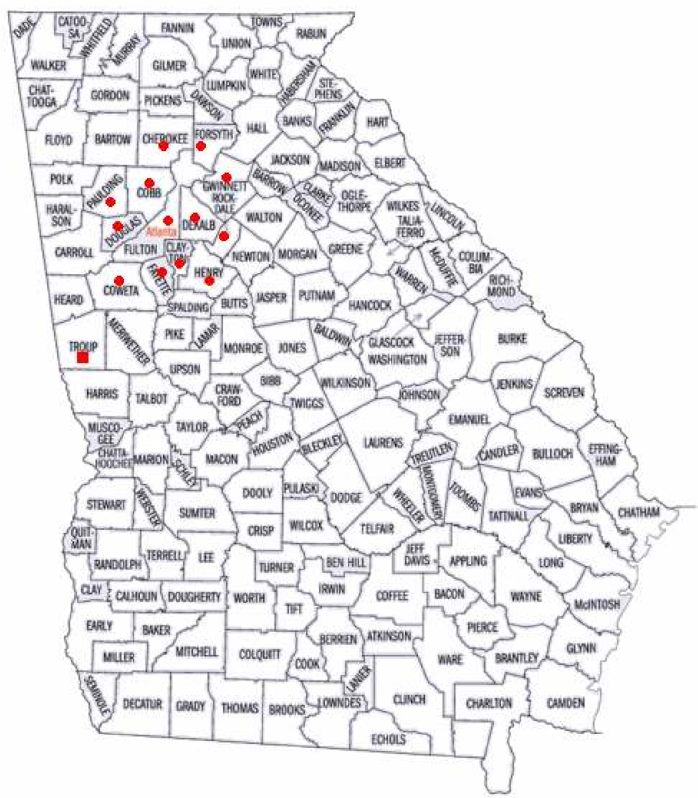


Figure 5.4: Counties and County Seats in Georgia

Table 5.6: Distances between County Seats and Recycling Facility in LaGrange, GA

County	County Seat	Lagrange, GA [miles]
Cherokee	Canton	103
Clayton	Jonesboro	62
Cobb	Marietta	83
Coweta	Newnan	31
DeKalb	Decatur	75
Douglas	Douglasville	64
Fayette	Fayetteville	52
Forsyth	Cumming	107
Fulton	Atlanta	67
Gwinnett	Lawrenceville	99
Henry	McDonough	83
Paulding	Dallas	91
Rockdale	Conyers	86

Based on the distances in Table 5.6, the truckload capacities found in Table 4.7, and the PIEs for PCC-tile detailed in Chapter 4, the graph in Figure 5.5 summarizes the total miles that the collected commercial PCC-tiles would travel during the collection process per year. The error bars correspond to the effects of upper and lower bounds for the PIEs on the total miles traveled for collection of PCC-tiles in the Atlanta region.

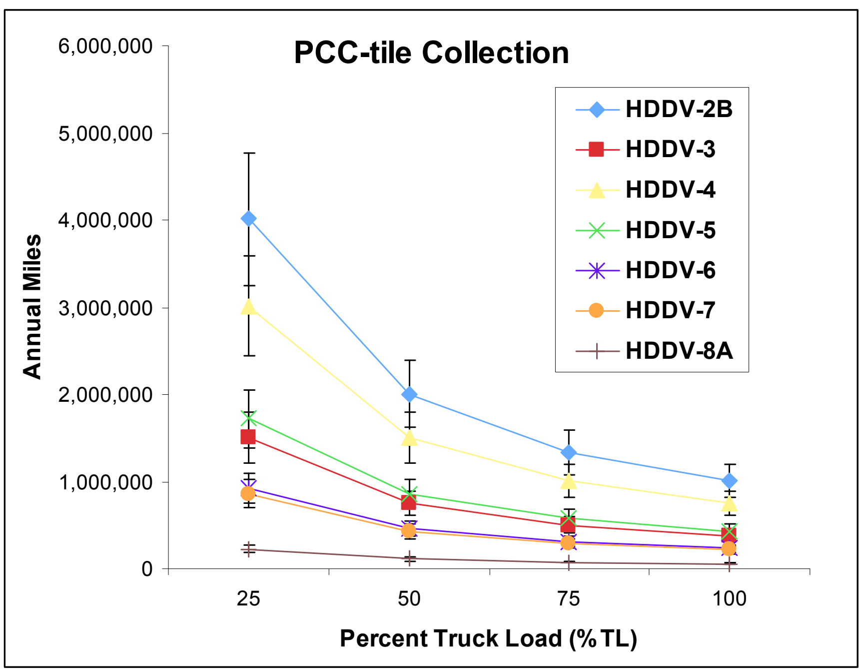


Figure 5.5: Annual Miles per HDDV for PCC-tile Collection

This collection strategy results in a great range of annual miles traveled. The minimum annual distance, achieved by using a HDDV-8A at 100%TL with the lower PIE bound, is 46,121 miles. The other end of the spectrum, using a HDDV-2B at 25%TL with the upper bound of the PIE, leads to 4,783,267 miles traversed annually. The differences in distance alone are quite large between vehicle and %TL chosen; thus, other factors must be considered in order to determine the appropriate representation for the PCC-tile collection strategy. One way to do this is to examine the economic and environmental impacts of each collection option; Figure 5.6 contains a cost versus CO_2 emissions comparison for all HDDVs for a range of %TL.

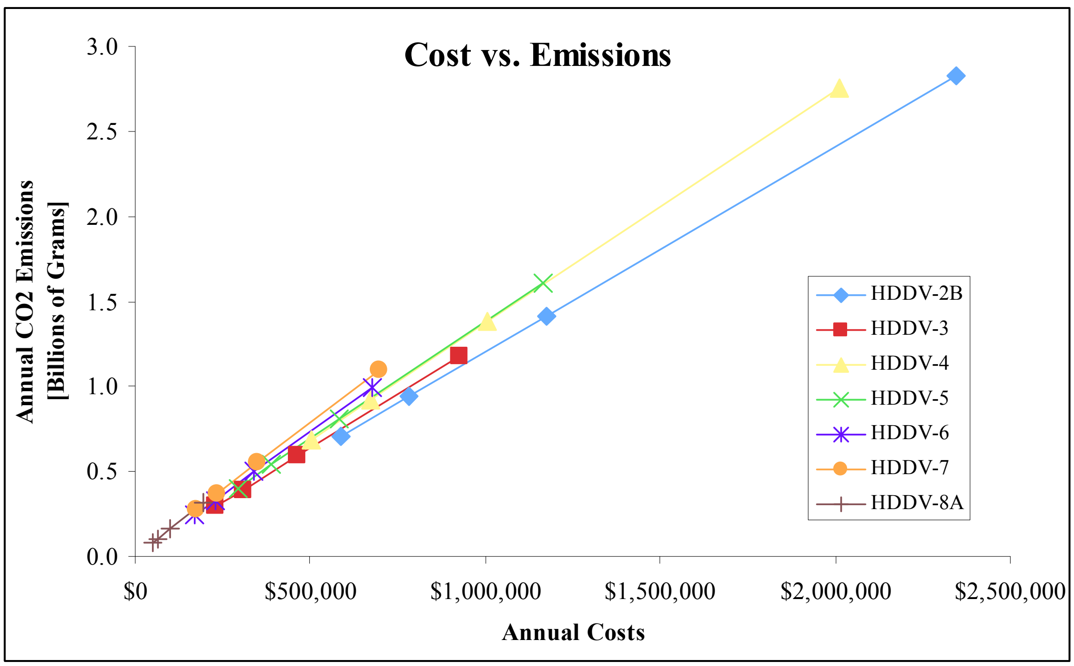


Figure 5.6: Cost versus CO_2 Emission of PCC-tile Collection

After examining the correlation between cost and CO_2 emissions represented in the graph above, the HDDV-3 at 75% TL are chosen to estimate the impacts of the collection phase of the PCC-tile material reclamation scenario because it is the smallest vehicle with the best emissions ratings whose FE and annual costs falls within the middle of the pack. Additionally, a 75% TL is chosen to estimate the amount of PCC-tile in transit per trip because it is unlikely that full TLs of PCC-tile would be collected throughout the year. Under these assumptions, the total miles traveled for collection of PCC-tiles is between 405,000 and 600,000 miles per year. This correlates to a cost range, which includes both fuel and labor costs, of $249,000 to $368,000 per year. This is approximately 5.6-8.3¢ per kg-PCC-tile collected. The environmental impacts of the PCC-tile collection strategy here are presented in Table 5.7.

Table 5.7: Annual Pollutant Emissions for PCC-tile Collection

HDDV-3 at 75%TL	Greenhouse Gases [kg-pollutant]			Criteria Pollutants [kg-pollutant]				Additional Pollutants [kg-pollutant]				
	CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
High	469,000	3	3	6	2900	N/R	11,000	N/R	N/R	950	70	N/R
Low	318,000	2	2	4	1200	N/R	7,600	N/R	N/R	640	50	N/R

5.2.1.2 <u>Post Consumer Carpet Tile Collection – Goodwill Scenario</u>

The second carpe-tile collection strategy being considered involves local drop-off sites concentrated in areas with high populations and thus high PIEs. A pre-existing set-up will be utilized here in order to explore the impacts of this type of dispersed collection on the overall EOL LCA. The Goodwill Industries, a nonprofit operation, offers a well integrated system of donation and retail locations into communities throughout the US. Thus, their existing donation centers and stores as potential collection sites for PCC will be leveraged for this study. In the Atlanta Metropolitan Region alone, there are a total of 44 donation centers and Goodwill stores (GII, 2005). Figure 5.7 provides an illustration of the 44 sites and their relative locations within the Atlanta Metropolitan Region using Google Maps. The dots in the bubble icons signify a donation center, and the lighter bubbles represent the Goodwill retail locations.

Figure 5.7: Goodwill Locations

In order to facilitate collection of the bulky carpe-tiles at a Goodwill site, a bin is required for storage. These bins come in a variety of sizes with maximum capacities between three and six tons and at various annual rental costs ranging from $5,350 to $5,475. Table 5.8: Bin Rental Capacities and Costs for bin capacity, size and annual rental rates. (Rapid Roll Offs: Dumpster Rental for Atlanta, 2008).


Figure 5.8: Collection Bins

Table 5.8: Bin Rental Capacities and Costs

Bin Size	Weight Capacity [kg]	Bin Dimensions [meters]	Bin Volume [cubic meters]	Annual Costs [$]
3 tons	2722	2.1 x 3.4 x 1.4	8.7	$5,350
4 tons	3629	2.4 x 3.7 x 1.5	13.6	$5,375
5 tons	4536	2.1 x 6.7 x 1.2	17.4	$5,425
6 tons	5443	2.4 x 6.7 x 1.8	30.0	$5,475

According to the PIEs discussed in Section 5.1.2, the average amount of carpet-tile disposed yearly in the Atlanta Metropolitan Region is around 4.4 million kg. Based on the PIEs and the storage bin capacities, the number of bins needed to collect all of the PCC-tile in the region for a range of pick-up schedules has been determined; these results are found in Table 5.16.

Table 5.9: Estimates of Sites Needed for Carpet Collection Based on Weight Capacity

Bin Size	Monthly	Twice Monthly	Weekly	Twice Weekly	Three Times Weekly	Four Times Weekly	Five Times Weekly	Six Times Weekly	Daily
3 tons	136	68	**32**	**16**	**11**	**8**	**7**	**6**	**5**
4 tons	102	51	**24**	**12**	**8**	**6**	**5**	**4**	**4**
5 tons	82	**41**	**19**	**10**	**7**	**5**	**4**	**4**	**3**
6 tons	68	**34**	**16**	**8**	**6**	**4**	**4**	**3**	**3**

If there are 44 potential collection sites, then a variety practical collection schedules exists based on the numbers of estimated open collection sites needed in Table 5.16; these scenarios are highlighted (i.e., not blacked out) in the table. Although there is clearly a lot of freedom in the number of site openings and collection schedules, the estimates in this study will focus mainly on weekly or twice weekly pick-up schedules. This allows for more geographically dispersed collections site throughout the metro region and a more consolidated pick-up schedule (Rapid Roll Offs: Dumpster Rental for Atlanta, 2008). The costs associated with the Goodwill collection scenario include, in addition to the bin rental fees, the fuel costs and the labor costs of the truck driver. These two additional costs are proportional to the distances traveled for collection and transportation to a recycling facility and the characteristics of the HDDV used. Based on bin sizes, only three HDDVs can even be considered according to their maximum loads. For a 3 ton bin, HDDVs-6, 7, and 8A can be used; for the 4, 5, and 6 ton bins only the HDDV-8A is large enough to carry the load. Thus, it is necessary to explore a variety of site openings in order to determine a best estimate for distances traversed and the consequential social, economic and environmental impacts. Additionally, it is also important to place the collection sites throughout the region in order to cater to the consumer and encourage the drop-off of PCC-tile at these sites as opposed to dumping the carpet at a local landfill. For the purposes of this study, it will be assumed that all bins placed at collection sites are the same size and all vehicles used to transport the collected material are of the same HDDV category. All distances are estimated using Google Maps, and it is assumed that the PCC-tile will be donated by the consumer and dropped-off at the closest open collection site. The exploration of these scenarios is carried out in MatLab. The code and distance matrices used for this analysis can be found in Appendix A.3 and A.4. The results, definitions and assumptions of the scenarios studied are presented in Table 5.17.

Table 5.10: Goodwill Annual Statistics Based on Number of Open Sites – PCC-tile

Number of Open Sites [units]	Scenario Description:	to Annual Distance [miles] to LaGrange,GA:	Annual Costs [$]
44	6 ton bins; all sites open	136,024	$353,830
44	5 ton bins; all sites open	162,568	$374,790
44	4 ton bins; all sites open	201,104	$406,180
23	6 ton bins; perimeter closed	129,834	$233,470
23	5 ton bins; perimeter closed	155,812	$254,980
23	4 ton bins; perimeter closed	193,604	$286,780
8	4 ton bins; greatest pop. open	204,124	$220,690
6	4 ton bins; greatest pop. open	206,682	$212,170
5	4 ton bins; greatest pop. open	205,758	$205,990
4	4 ton bins; greatest pop. open	203,258	$198,440

The spread of open sites ranging from 4 to 44 results in an annual distance swing of over 77,000 which translates to approximate transportation cost differences near $67,000; these estimates are absolute and do not factor bin size into the equation. If the annual bin rental costs are included in these differences, then the annual cost difference between 4 and 44 open collection sites is around $208,000; again, no distinction between bin size is accounted for here. Thus, it appears that the cost associated with bin rentals overshadows the cost resulting from the additional miles traveled for collection by a little less than 70%. Bin size, however, does play a significant role in the collection scheme comparisons for PCC-tile. The bin size (for 23 and 44 open sites) effects the total miles traveled by about 64,000 and annual costs by approximately $53,000. Therefore, some compromise between the number of open sites, the bin size, and the annual distance traversed must be made. Based on cost alone, the 4 sites with 4 ton bin capacities is the most attractive collection option. The scenario with the least environmental impacts, based on total miles traversed, is the 23 site with 6 ton bin capacities option. The mileage difference between this scenario and the economically preferred scenario is approximately 73,000 miles; the annual cost difference is around $35,000. And, based on the mileage difference, it translates to a potential employment difference of 1,300 hours and $22,000 wage pay annually, which is approximately 63% of the total cost difference. This relationship is classic example of the trade-offs between economics, the environment, and social (labor potential) impact.

5.2.1.3 Post Consumer Carpet Tile Collection – Summary

There are several ways to assess the collection schemes previously discussed in this section for the collection of PCC-tile. The first comparison can be conducted across the "most practical" of each of the collection schemes, which would include the use of the HDDV and %TL that most closely mimics reality. However, the second comparative method involves an assessment across the collection schemes all with identical vehicular assumptions, i.e. same HDDV and %TL. Additionally, the comparative analysis must include the diversity of collection impacts based on the various geographically dispersed collection schemes dur to the variation in annual miles and annual costs based on collection bin size. In doing this multi-scenario comparison, there are drastically different preferred collection schemes for PCC-tile in the Atlanta Metropolitan Region. Therefore, it is necessary to reconcile some of these differences and to come up with a reasonable estimate for the collection based LCI to be used in the overall EOL comparative assessments that are to follow.

The results of the comparisons method are found in Figure 5.9 and Figure 5.10. There is clearly some variance in annual impacts resulting from the various scenarios. The cheapest scenario with the least environmental impacts (based on annual miles) is the county seat scenario with the HDDV-8A @ 100%TL. This result makes sense considering the capacity of the HDDV-8A vehicles. However, it is unlikely that in reality full TLs of material would be colleted at once and transported in bulk to LaGrange. Therefore, the alternate county seat scenario is assumed to represent reality more closely. Comparing the county seat with the HDDV-3 @ 75%TL scenario with the geographically dispersed collection schemes, the dispersed collection schemes scenarios appear to be the preferred option in both economic and environmental impacts. They represent annual savings of 308,000-381,000 miles and $81,000-$116,000.

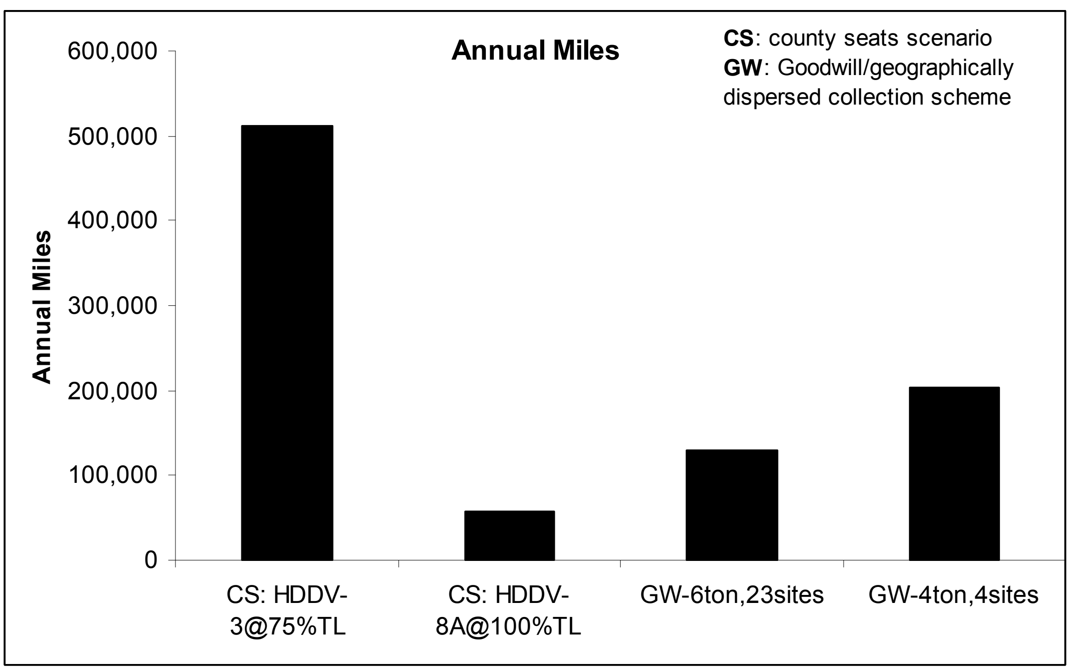


Figure 5.9: PCC-tile Collection Comparison by Miles

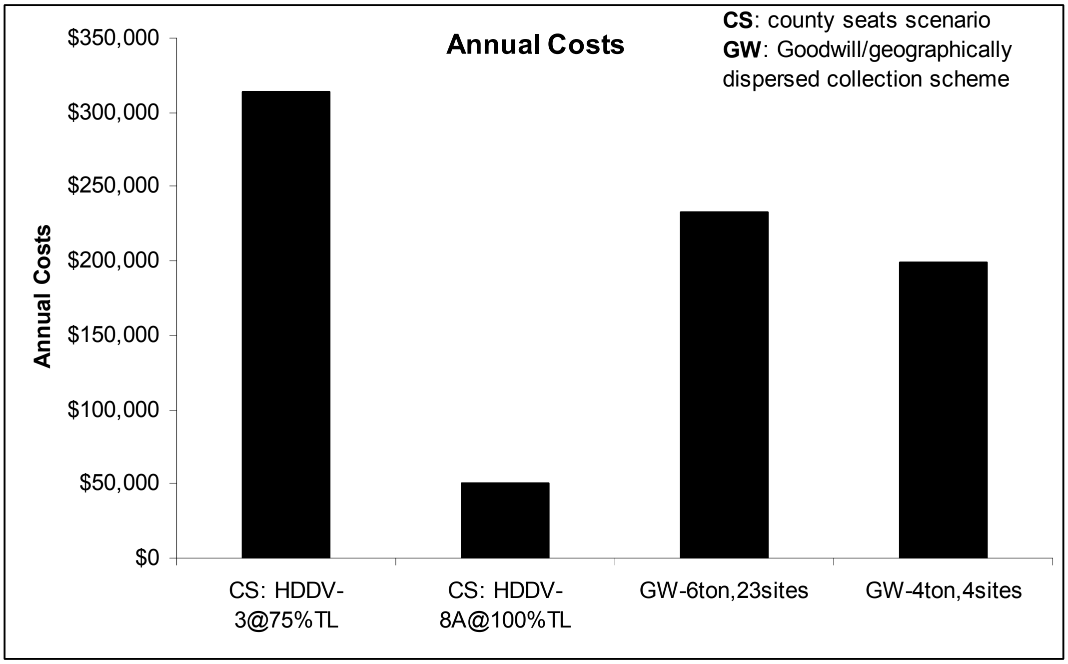


Figure 5.10: PCC-tile Collection Comparison by Cost

For this study, the primary collection scheme will be the county seats with HDDV-3 @ 75%TL estimation. Although this is the highest among the summarized alternatives, it will provide an upper bound on the PCC-tile collection impacts. The effects of alternative collection schemes, and impacts resulting from lower annual miles traversed and reductions in annual collection costs, will be assessed during the comparative impact assessment discussed in Chapter 9. In the following tables, the environmental, economic and social impacts for the various PCC-tile collection schemes are summarized.

Table 5.11: Annual Pollutant Emissions for PCC-tile Collection[7]

	Greenhouse Gases [g-pollutant]			Criteria Pollutants [g-pollutant]				Additional Pollutants [g-pollutant]				
	CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
low	184,234,446	649	649	2,337	1,367,152	N/R	5,297,227	N/R	N/R	444,032	33,757	N/R
middle	288,423,102	1,016	1,016	3,659	2,140,307	N/R	8,292,926	N/R	N/R	695,142	52,847	N/R
high	400,181,387	2,555	2,555	5,111	2,483,884	N/R	9,633,996	N/R	N/R	807,518	61,330	N/R

[7] Estimates used here for the upper collection bounds are based on the average PIEs for PCC-tile in the Atlanta Metropolitan Region, discussed in Section 5.1.2. The variability of the PIEs translates into an 18% swing on the upper estimates for the collection LCI.

Table 5.12: Annual LCI Categories for PCC-tile Collection[8]

Category	Low	Middle	High
Truck Specifications	HDDV-8A @ 100%TL	HDDV-8A @ 100%TL	HDDV-3 @ 75%TL
Total Miles	129,834	203,258	511,087
Bin Rental Costs [$]	$125,925	$21,496	N/A
Fuel Costs [$]	$74,005	$115,857	$159,756
Labor Costs [$]	$39,186	$61,347	$154,255
Total Costs [$]	$239,116	$198,700	$314,011

5.2.2 Broadloom Carpet Collection

There are several plausible scenarios for estimating the annual collection miles traversed for the reclamation of broadloom carpets. The most generic representation is explored in Section 5.2.2.1, where the collection scheme is captured as the distances between county seats and recycling facilities. A further refinement of the collection strategy is discussed in Section 5.2.2.2; where a more geographically dispersed scenario is explored by estimating the distances between every zip code in the Atlanta metropolitan region and the regional carpet recycling facilities. Lastly, a scenario involving geographically dispersed collection sites represented by Goodwill Donation and Retail Centers and the distances between these sites and the recycling facilities is explored in Section 5.2.2.3.

5.2.2.1 County Seats

Much like the collection scenario for PCC-tiles described in Section 5.2.1, the county seats of each of the 13 counties in the Atlanta metropolitan region are used here as a generic means of capturing the potential annual collection mileage for broadloom carpet collection. Figure 5.11 contains a graph estimating the annual miles traveled to collect all of the broadloom carpet concentrated at the county seats and transported to a recycling facility in Calhoun, GA, and Figure 5.12 estimates the annual distances for collection from each county seat to a recycling facility in Dalton, GA. These annual estimates are based on the distances obtained with Google Maps and presented in Table 5.6. Again, both graphs are used to explore the effects of HDDV capacity and %TL on the total annual mileage. This results in annual distances ranging from 380,000 to 41,000,000 miles for collection and transportation to Calhoun and distance of 480,000 to 51,000,000 miles for collection and transportation to Dalton. These two magnitudes of differences in annual mileage estimates is due in large part to the shear quantity of materials to be collected and the significant differences in truck capacity.

Table 5.13: Distances between County Seats and Recycling Facility in Calhoun and Dalton, Georgia

County	County Seat	Calhoun, GA [miles]	Dalton, GA [miles]
Cherokee	Canton	46	64
Clayton	Jonesboro	89	107
Cobb	Marietta	54	71
Coweta	Newnan	105	123
DeKalb	Decatur	75	93
Douglas	Douglasville	62	80
Fayette	Fayetteville	93	111
Forsyth	Cumming	68	86
Fulton	Atlanta	71	89
Gwinnett	Lawrenceville	89	107
Henry	McDonough	100	118
Paulding	Dallas	52	70
Rockdale	Conyers	96	113

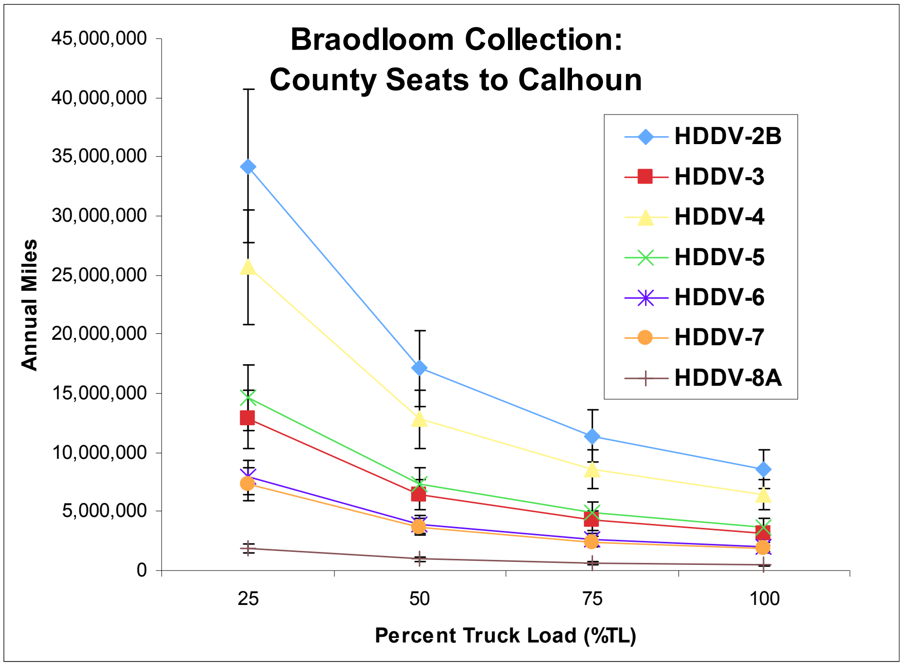


Figure 5.11: Annual Miles per HDDV for Braodloom Collection from County Seats to Calhoun, Georgia

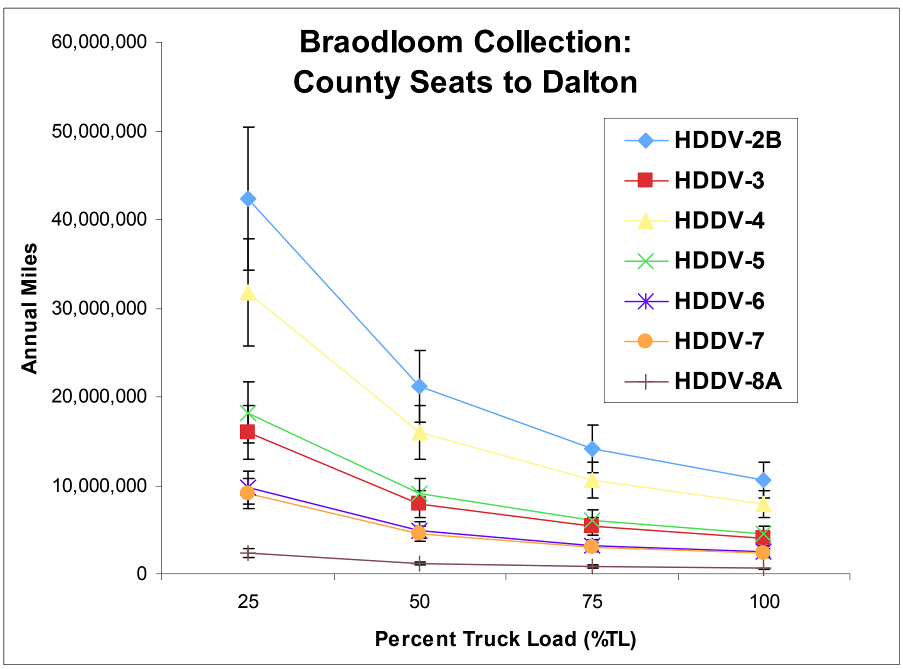


Figure 5.12: Annual Miles per HDDV for Braodloom Collection from County Seats to Dalton, Georgia

Using the same assumptions discussed in Section 5.2.1, HDDV-3 vehicles at 75%TL will be used for this collection strategy. This leads to annual miles traversed for collection and transportation of broadloom carpet to Calhoun between 3.5 and 5.1 million and between 4.3 and 6.3 million for collection and transportation to Dalton. This correlates to annual costs of $4.9 to $7.2 million and $6.0 to $8.9 million for collection and transportation to Calhoun and Dalton respectively. The environmental impacts of the PCC-broadloom collection discussed here are presented in **Error! Reference source not found.**.

Table 5.14: Annual Pollutant Emissions for PCC-broadloom Collection

HDDV-3 at 75%TL		Greenhouse Gases [kg-pollutant]			Criteria Pollutants [kg-pollutant]				Additional Pollutants [kg-pollutant]				
		CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
Calhoun	High	4,000,000	25	25	51	24762	N/R	96,000	N/R	N/R	8,050	610	N/R
	Low	2,700,000	17	17	35	16776	N/R	65,000	N/R	N/R	5,450	410	N/R
Dalton	High	4,950,000	32	32	63	30721	N/R	119,000	N/R	N/R	10,000	760	N/R
	Low	3,350,000	21	21	43	20813	N/R	81,000	N/R	N/R	6,800	510	N/R

5.2.2.2 Zip Codes

Another more dispersed representation of the collection of broadloom carpet in the Atlanta Metropolitan Region is to estimate the distance traversed during collection from the individual zip codes to the recycling facilities. In the metropolitan region of Atlanta there are 142 different zip codes. For a complete list of distances between the 142 zip codes and the recycling facilities in Calhoun and Dalton, Georgia, refer to Appendix A.2. The annual estimated mileage per year for all of the HDDVs considered over a range of %TL for collection and transportation of broadloom carpet to Calhoun and Dalton are found in Figure 5.13 and Figure 5.14 respectively.

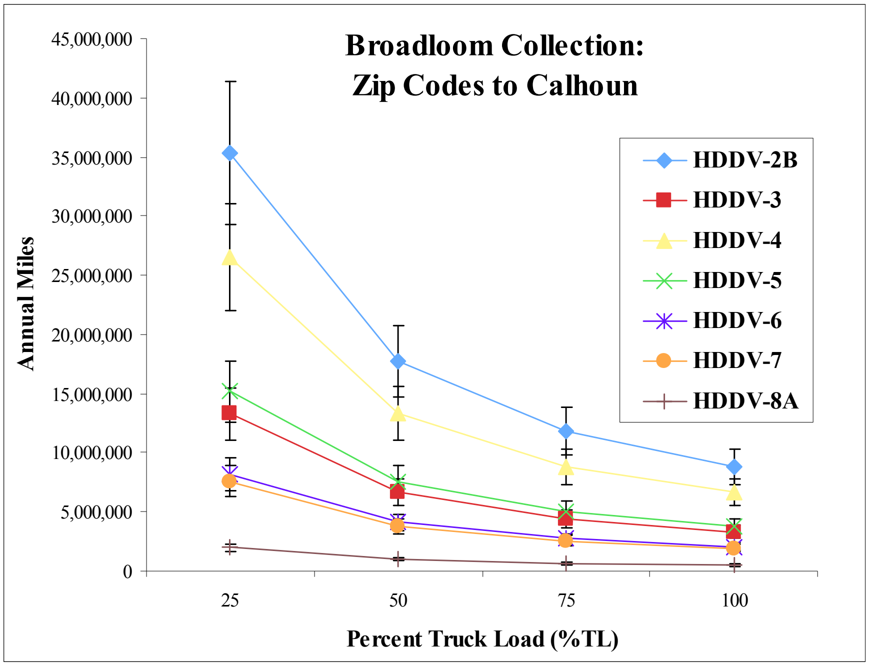


Figure 5.13: Annual Miles per HDDV for Braodloom Collection from Zip Codes to Calhoun, Georgia

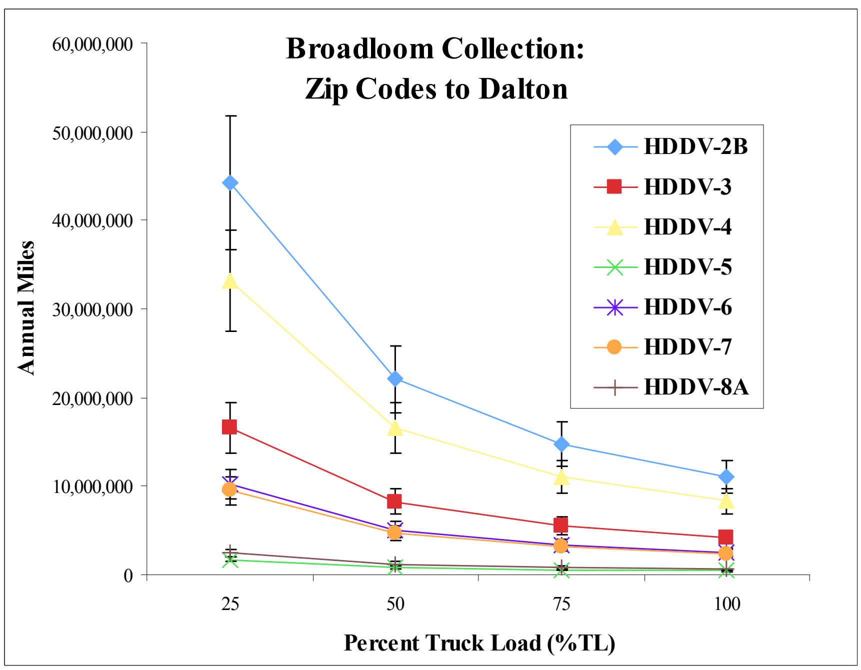


Figure 5.14: Annual Miles per HDDV for Braodloom Collection from Zip Codes to Dalton, Georgia

Again, using HDDV-3s at 75%TL leads to annual miles traversed for collection and transportation of broadloom carpet from each zip code to Calhoun between 3.7 to 5.2 million and between 4.6 to 6.5 million for collection and transportation to Dalton. This correlates to annual costs of \$5.2 to \$7.3 million and \$6.5 to \$9.1 million for collection and transportation to Calhoun and Dalton respectively. The environmental impacts of the PCC-broadloom collection strategy discussed here are presented in Table 5.15.

Table 5.15: Annual Pollutant Emissions for PCC-broadloom Collection

HDDV-3 at 75%TL		Greenhouse Gases [kg-pollutant]			Criteria Pollutants [kg-pollutant]				Additional Pollutants [kg-pollutant]				
		CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
Calhoun	High	4,040,000	26	26	52	25,100	N/R	97,300	N/R	N/R	8,160	620	N/R
	Low	2,890,000	18	18	37	17,900	N/R	69,600	N/R	N/R	5,830	440	N/R
Dalton	High	5,050,000	32	32	65	31,400	N/R	121,700	N/R	N/R	10,200	775	N/R
	Low	3,610,000	23	23	46	22,400	N/R	87,000	N/R	N/R	7,290	555	N/R

5.2.2.3 Geographically Dispersed Collection Sites

The third broadloom carpet collection strategy being considered involves local drop-off sites concentrated in areas with high populations and thus high PIEs. The pre-existing set-up of the Goodwill Industries donation and retail centers will again be leveraged as potential collection sites for PCC in this study (GII, 2005). In order to facilitate collection of the bulky broadloom carpet at a Goodwill site, a bin is required for storage. Refer to Table 5.8: Bin Rental Capacities and Costs for bin capacity, size and annual rental rates. (Rapid Roll Offs: Dumpster Rental for Atlanta, 2008). According to the PIEs discussed in Section 5.1.2, the average amount of broadloom carpet disposed yearly in the Atlanta Metropolitan Region is around 47 million kg. Based on the PIEs and the storage bin capacities, the number of bins needed to collect all of the PCC-broadloom in the region for a range of pick-up schedules has been determined; these results are found in Table 5.16.

Table 5.16: Estimates of Sites Needed for Carpet Collection Based on Weight Capacity

Bin Size	Monthly	Twice Monthly	Weekly	Twice Weekly	Three Times Weekly	Four Times Weekly	Five Times Weekly	Six Times Weekly	Daily
3 tons	1428	714	330	165	110	83	66	55	47
4 tons	1071	536	248	124	83	62	50	**42**	**36**
5 tons	857	429	198	99	66	50	**40**	**33**	**29**
6 tons	714	357	165	83	55	**42**	**33**	**28**	**24**

If there are 44 potential collection sites, then only a few practical collection schedules exist based on the numbers of estimated open collection sites needed in Table 5.16; these scenarios are highlighted in the table. There is clearly more site freedom associated with the use of a 6 ton bin, however these bins are slightly more expensive (Rapid Roll Offs: Dumpster Rental for Atlanta, 2008). The costs associated with the Goodwill collection scenario also include fuel costs and the labor costs of the truck driver. These two additional costs are proportional to the distances traveled for collection and transportation to a recycling facility and the characteristics of the HDDV used. Based on bin sizes, only three HDDVs can even be considered according to their maximum loads. For a 3 ton bin, HDDVs-6, 7, and 8A can be used; for the 4, 5, and 6 ton bins only the HDDV-8A is large enough to carry the load. Thus, it is necessary to explore a variety of site openings in order to determine a best estimate for distances traversed and the consequential social, economic and environmental impacts. Additionally, it is also important to place the collection sites throughout the region in order to cater to the consumer and encourage the drop-off of PCC-broadloom at these sites as opposed to dumping the carpet at a local landfill. For the purposes of this study, it will be assumed that all bins placed at collection sites are the same size and all vehicles used to transport the collected material are of the same HDDV category. All distances are estimated using Google Maps, and it is assumed that the PCC-broadloom will be disposed of by the consumer at the closest open collection site. The exploration of these scenarios is carried out in MatLab. The code and distance matrices used for this analysis can be found in Appendix A.3 and A.4. The results, definitions and assumptions of the scenarios studied are presented in Table 5.17.

Table 5.17: Goodwill Annual Statistics Based on Number of Open Sites

Number of Open Sites [units]	Scenario Description:	to Facility in GA:	Annual Distance [miles]	Annual Costs [$]
44	all possible sites open	Dalton	1,608,940	$1,636,000
		Calhoun	1,268,024	$1,339,200
43	site 26 closed; no carpet collected	Dalton	1,380,342	$1,437,000
		Calhoun	1,087,864	$1,183,400
41	outermost sites closed; average of variety of combinations	Dalton	1,376,525	$1,422,450
		Calhoun	1,083,676	$1,167,825
40	business zip codes without population data closed	Dalton	1,381,886	$1,421,900
		Calhoun	1,089,410	$1,167,300
32	perimeter sites closed	Dalton	1,366,654	$1,364,900
		Calhoun	1,074,186	$1,110,300
27	perimeter sites closed	Dalton	1,358,542	$1,330,400
		Calhoun	1,066, 094	$1,075,900
23	perimeter sites closed	Dalton	1,359,084	$1,309,000
		Calhoun	1,069,238	$1,056,700

The spread of open sites ranging from 23 to 44 results in an annual distance swing of over 250,000 miles to Dalton and 202,000 miles to Calhoun which translates to approximate transportation cost differences of over $218,000 and $176,000 respectively. If the annual bin rental costs are included in these differences, then the annual cost difference between 23 and 44 open collection sites is over $327,000 for transportation to Dalton and $282,000 for transportation of Calhoun. Thus, it appears that the cost associated with bin rentals overshadows the cost resulting from the additional miles traveled for collection by 50% to 60%. Therefore, some compromise between the number of open sites and the annual distance traversed must be found; this tradeoff is plotted in Figure 5.15. It becomes apparent that there is not much variance in annual distances traveled for scenarios ranging from 23 to 41 open sites. This is illustrated in Figure 5.16. But, as Figure 5.17 shows, the cost trade-off for the number of open sites grows linearly with the number of open sites. Therefore, the optimal number of open sites that would collect PCC-broadloom carpet in 6ton bins is 23. This translates to an average daily pick-up schedule.

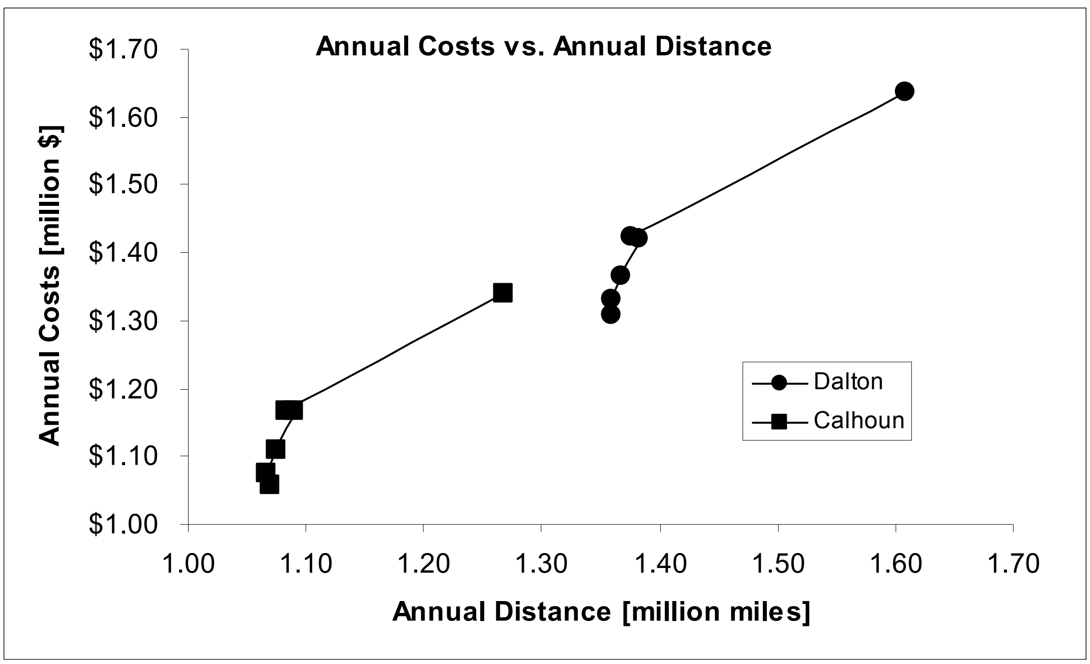


Figure 5.15: Annual Costs versus Annual Distance Traveled for Goodwill Collection Scheme

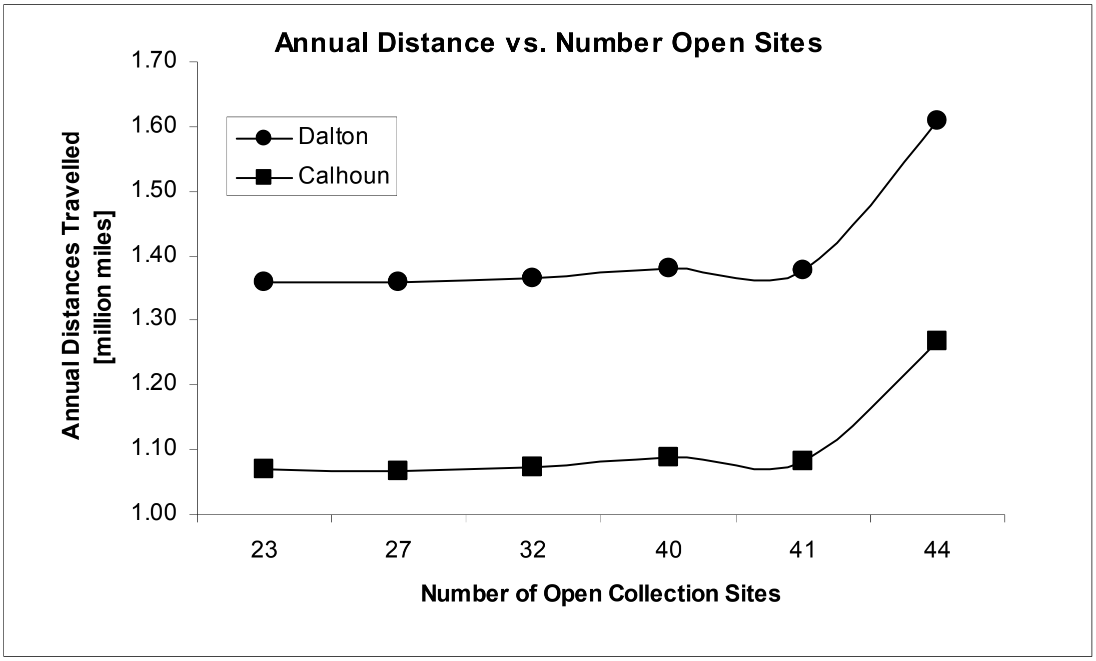


Figure 5.16: Annual Distances Traveled versus Number of Open Collection Sites for PCC-Broadloom

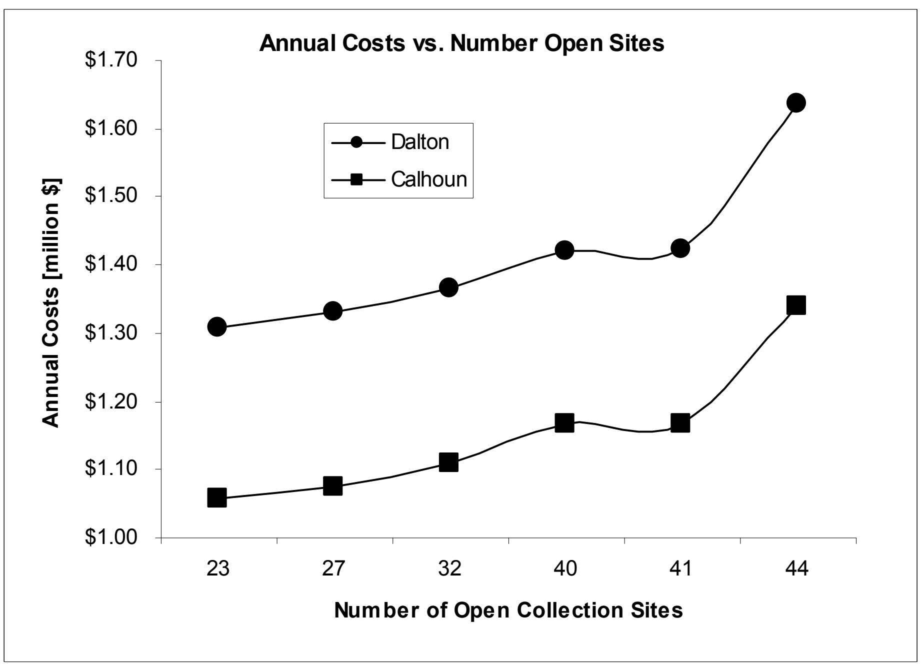


Figure 5.17: Annual Costs versus Number of Open Collection Sites for PCC-Broadloom

5.2.2.4 Broadloom Carpet Collection Schemes Compared

There are two ways to assess the collection schemes previously discussed in this chapter for the collection of PCC-broadloom carpet. The first comparison can be conducted across the "most practical" of each of the collection schemes, which would include the use of the HDDV and %TL that most closely mimics reality. However, the second comparative method involves an assessment across the collection schemes all with identical vehicular assumptions, i.e. same HDDV and %TL. In doing this dual approach comparison, there are drastically different preferred collection schemes for PCC-broadloom in the Atlanta Metropolitan Region. Therefore, it is necessary to reconcile some of these differences and to come up with a reasonable estimate for the collection based LCI to be used in the overall EOL comparative assessments that are to follow.

The results of the first comparative method are found in Figure 5.18 and Figure 5.19. In this comparison, the HDDV-3 @ 75%TL is used for the County Seat and Zip Code estimation methods, while the HDDV-8A @ 100%TL is assumed for the Goodwill scenario (for an explanation of these assumptions and decisions refer to Sections 5.2.2.1, 5.2.2.2, and 5.2.2.3 respectively). In this scenario, there is only a 4% difference in annual distance and cost for the County Seat and Zip Code collection estimation methods. However, there is a 75% distance savings and 80% cost savings between the Goodwill scheme and the average estimates of the County Seat and Zip Code scheme. Unfortunately, these findings are not supported by the second comparison method. Figure 5.20 and Figure 5.21 contain the results of the collection comparison based on identical vehicle and %TL usage. In this scenario, it is the Zip Code and Goodwill schemes that are neck in neck with an approximate 2% difference in annual miles and 16% cost difference. It is the County Seat estimation that demonstrates an annual distance reduction around 20% and a cost reduction around 30%.

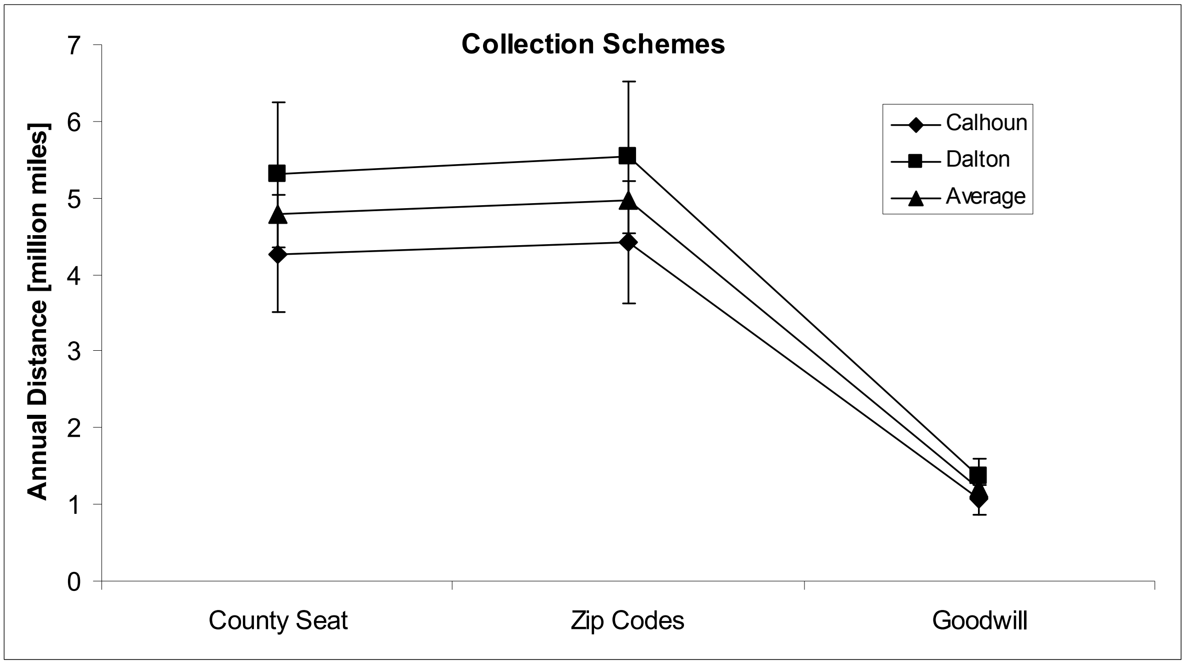


Figure 5.18: PCC-broadloom Collection Comparison - Varying HDDV and %TL by Scenario

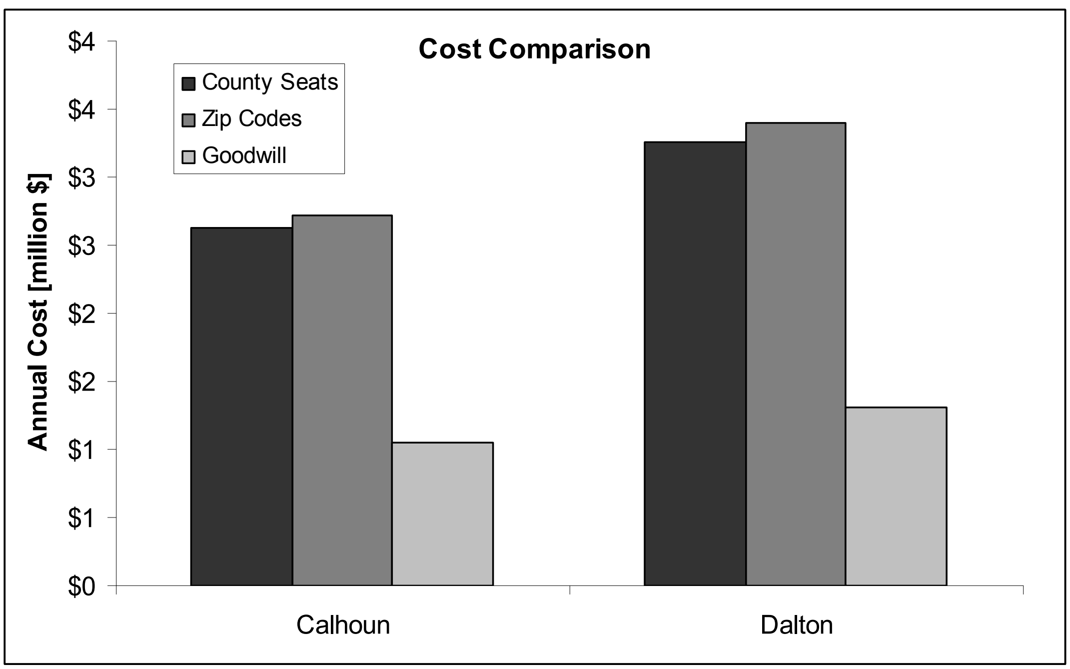


Figure 5.19: PCC-broadloom Collection Cost Comparison - Varying HDDV and %TL by Scenario

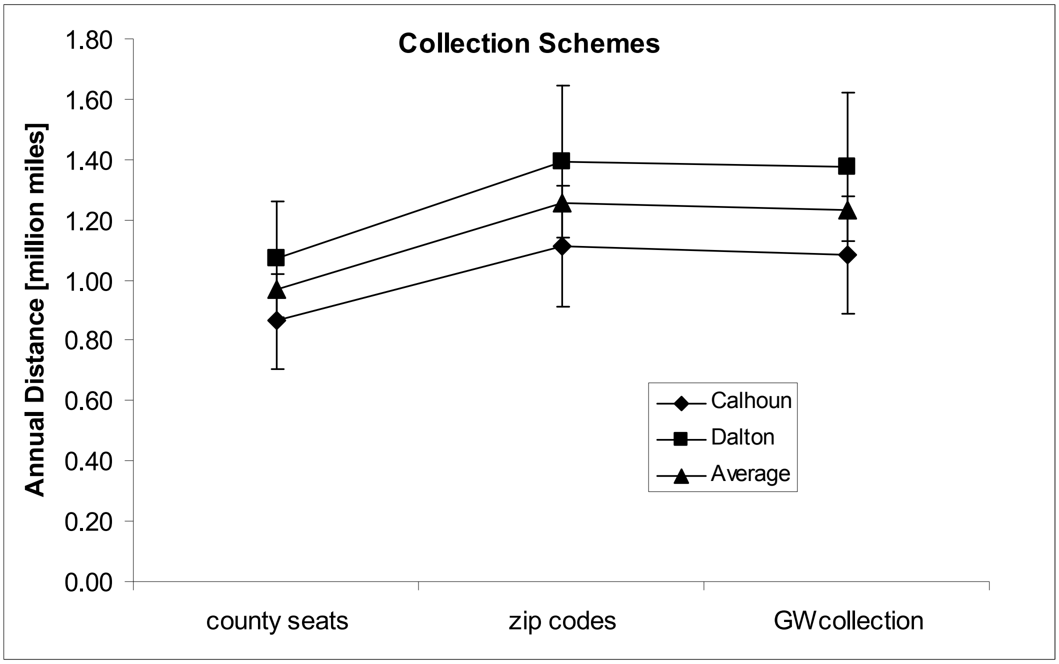


Figure 5.20: PCC-broadloom Collection Comparison – HDDV-8A @ 100%TL

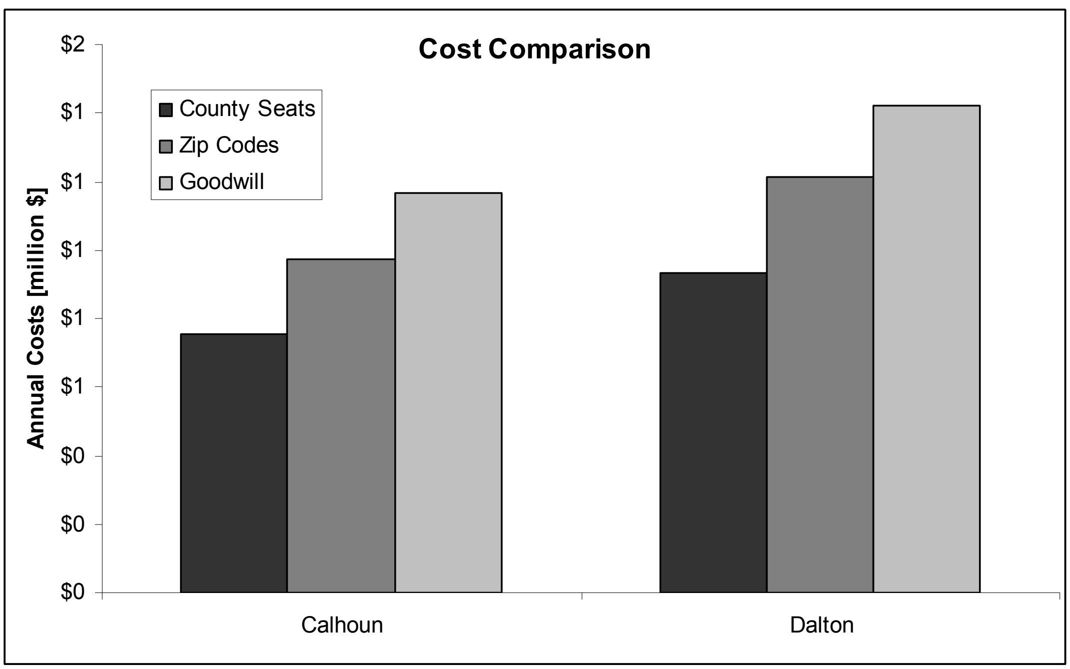


Figure 5.21: PCC-broadloom Collection Cost Comparison – HDDV-8A @ 100%TL

Although the second comparative method leads to less deviation in the annual distance and cost estimates for the collection scheme, the underlying assumptions of uniform vehicle and TL is not as accurate a representation of reality as the collection schemes which utilize vehicle characteristics which more closely reflect a real-life scenario. Therefore, as a basis for PCC-broadloom collection the results of the first comparative method will be used and the annual distance average of PCC collection between Calhoun and Dalton will be employed. However, in order to assess the overall impact of an improved collection scheme on the various EOL scenarios explored later, the Goodwill estimation will be used as a lower bound. The environmental LCI for the collection of PCC-broadloom is summarized in Table 5.18 and the remaining impact factors are included in Table 5.19.

Table 5.18: Annual Pollutant Emissions for PCC-broadloom Collection[8]

	Greenhouse Gases [g-pollutant]			**Criteria Pollutants** [g-pollutant]				**Additional Pollutants** [g-pollutant]				
	CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
low	1,745,000,000	6,150	6,150	22,140	12,952,000	N/R	50,183,000	N/R	N/R	4,206,000	320,000	N/R
high	3,824,000,000	24,420	24,420	48,840	23,738,000	N/R	92,070,000	N/R	N/R	7,717,000	586,000	N/R

[8] Estimates used here for the upper collection bounds are based on the average PIEs for PCC-broadloom in the Atlanta Metropolitan Region, discussed in Section 5.1.2. The variability of the PIEs translates into an 18% swing on the upper estimates for the collection LCI.

Table 5.19: Annual LCI Categories for PCC-Broadloom Collection[8]

Category	Low	High
Truck Specifications	HDDV-8A @ 100%TL	HDDV-3 @ 75%TL
Total Miles	1,229,964	4,884,358
Bin Rental Costs [$]	$125,925	$0
Fuel Costs [$]	$701,079	$1,526,756
Labor Costs [$]	$371,225	$1,474,188
Total Costs [$]	$1,198,230	$3,000,944

5.2.3 Introduction of Central Warehouse

A major contributor to the overall burden of collection is the shear amount of material that is being transported from the Atlanta Metropolitan Region out to the recycling facilities throughout Georgia. This burden is magnified on a per-kilogram reclaimable or reusable material basis by the fact that much of the material collected is then transported directly to a landfill near the recycling facility because it has no recyclable value. The material being disposed of is either not recyclable in general or is not recyclable at the particular facility. For example, PCC-tile is only recycled in LaGrange. Additionally the final recycled-content products produced at the facilities differ and thus are each associated with a unique economic model which ultimately affects the results of the TBL assessment of the various EOL scenarios. Therefore, each scenario could be improved overall if only the material sent to each recycling facility was the material that is actually recycled at the given facility. This would eliminate the need to transport waste across the state and could potentially result in lower environmental and economic burdens. However, this reduction in negative impact is not a guarantee because the actual construction, maintenance and operations associated with a centralized warehouse that would facilitate the collection and sorting of the PCC would have an impact on the overall TBL of the scenario. Thus, it is imperative that a comparative analysis be conducted in order to assess the impacts associated with the installation and operations of a new warehouse facility within the Atlanta Metropolitan Region as opposed to hauling all PCC collected, recyclable and not, to the desired recycling facility to be sorted and processed on the existing sites.

In order to determine the impact of installing a new warehouse within the Atlanta Metropolitan Region it is important to capture the approximate size of the facility, the primary material composition, and the consequential impacts of the installation. According to the EIA's Energy Consumption Survey based on 2003 Commercial Building Data, it is estimated that the national average building floor space for Warehouse and Storage buildings is around 16,900ft^2 (1,570m^2). These buildings are defined as those that store goods, manufactured products, and/or raw materials; it also includes distribution and shipping centers. To further refine the building estimates, data for the South Atlantic Census region shows that the average Warehouse & Storage facility for the region is approximately 14,688ft^2 (1,365m^2) (EIA, 2003). Additionally, according to an article in *Supply Chain Digest*, the typical height of a warehouse is between 24-26ft (7.3-7.9m) in order to clear a 4-high average size pallet storage rack (SupplyChainDigest, 2007). Therefore, an average warehouse facility floor space of 1,400m^2 with dimensions of 40m x 35m and total wall space and an average height of 8m to grossly estimate the quantity of construction materials needed to build a new warehouse within the Atlanta Metropolitan Region will be used.

To estimate the environmental impacts associated with building a new warehouse, the material composition statistics reported by the EIA for warehouses on a national level are used here[9]. The most predominant material used for exterior warehouse walls is metal panels and for roofing is metal surfacing. Therefore, the BEES environmental estimates for generic aluminum siding will be used to represent both the wall and roof construction materials. It will also be assumed that the warehouse will sit on a typical slab-on-grade foundation where the concrete is mixed and poured on site. The environmental outputs associated with the manufacturing and installation of these materials are found in the Table 5.20, and the total environmental impacts of a new warehouse based solely on average size and typical materials is located Table 5.21.

Table 5.20: Environmental Impacts of New Warehouse Materials

	Greenhouse Gases [g-pollutant/m^2]			Criteria Pollutants [g-pollutant/m^2]					Additional Pollutants [g-pollutant/m^2]			
Materials	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
slab: cement	43,260	44	0.58	114	170	0	119	0	0.002	12	244	0
walls & roof: aluminum shingles	10,269	26	0.04	80	27	0	110	0	0.0002	5	0.06	0

Table 5.21: Environmental Impact of New Warehouse Construction

Greenhouse Gases [g-pollutant/warehouse]			Criteria Pollutants [g-pollutant/warehouse]					Additional Pollutants [g-pollutant/warehouse]			
CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
87,263,000	130,000	915	368,000	307,000	0	454,000	0	4	30,000	341,000	0

Building a warehouse is environmentally costly, and the assumptions made here are an underestimation of the environmental investment required of new construction. However, it does provide a basis for comparison against the potential savings or losses when compared to the current collection schemes. Ideally, a central warehouse would store and sort the PCC collected in order to aggregate collection and thus send out higher

[9] The statistics for building materials specific to warehouse and storage facilities are not available at the Census Region level.

%TLs of materials to the recycling facilities. Additionally, a central sorting site would lead to more efficient transportation of materials in that only the recyclable materials at a given facility would be driven to that particular facility. In other words, it eliminates the transportation of materials that will only be further transported to a landfill because they are not recyclable. There is also the potential to do some of the mechanical material size reduction and separation at the central warehouse which would further segregate the recyclable materials and eliminate even more fruitless transportation of waste materials.

In order to assess the environmental differences between the collection scenarios previously discussed in this chapter and the introduction of a central storage and sorting warehouse, I have converted the environmental impacts of the warehouse to equivalent miles traveled by both HDDV-3s and HDDV-8As. This equivalency demonstrates the mileage that would need to be conserved in order to environmentally support the construction of a new warehouse for carpet collection. The results of this comparison are found in Table 5.22.

Table 5.22: Environmental Impacts of New Warehouse Materials

	Greenhouse Gases			Criteria Pollutants					Additional Pollutants			
	CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
Warehouse [g-pollutant]	8,7263,000	130,000	915	368,000	307,000	0	454,000	0	4	30,000	341,000	0
HDDV-3 [Equivalent Miles]	111,000	25,946,000	183,000	40,844,000	63,000	N/R	24,000	N/R	N/R	19,000	2,844,000	N/R
HDDV-8A [Equivalent Miles]	61,000	25,946,000	183,000	20,422,000	29,000	N/R	11,000	N/R	N/R	9,000	1,312,000	N/R

The range of equivalent miles per individual pollutant impact category is quite large spanning 9,000 to 41 million miles for HDDV-3s and 9,000 to 26 million miles for HDDV-8As. If examined from an aggregated environmental impact perspective (i.e., compare GWP, CAPs, Smog Potential, and EcoToxicity) the mileage spread is a little more narrow ranging from 56,000 to 1.4 million and 26,000 to 645,000 miles for HDDV-

3 and HDDV-8As respectively. All of the results for this comparison are found in Table 5.23.

Table 5.23: Aggregated Environmental Impact Mile Equivalents

	GWP	CAPs	Smog Potential	EcoToxicity
Warehouse [g-pollutant-equivalents]	90,517,000	21,000	425,000	473,000
HDDV-3 [Equivalent Miles]	115,000	1,395,000	56,000	1,253,000
HDDV-8A [Equivalent Miles]	64,000	645,000	26,000	579,000

Referring back to the earlier collection scenarios discussed in this chapter, annual collection miles range from 1.2-4.9 million miles for PCC-broadloom collection and 405,000-600,000 miles for PCC-tile. If the total PCC collection mileage is aggregated, the resulting annual average is 3,552,500 miles; therefore, a distances savings of 20% and 40% for HDDV-8A and HDDV-3 use respectively would need to be achieved in order to justify the construction of a new warehouse. This distance savings translates into potential fuel cost savings of over $403,000 and lost transportation wages of over $308,000. These lost wages could be recouped by employment at the warehouse. If the average hourly wage rate for the employees at the warehouse is around $13.21 based on BLS data for *Textile Machine Setters, Operators, and Tenders* (SOC code: 51-6062), an estimated 3,000 8-hr. shifts would have to be created (BLS, 2007). Running two shifts a day, two people per shift, seven days a week, the employment potential would be recaptured in two years time.

Considering all of these factors, the payback period for a central warehouse storage and sorting center would be realistically fall somewhere between 3-5years. Traditionally, shorter return-on-investments are desired when money is involved; however, with more global goals of environmental improvement, the 3-5years of recouped environmental expenses seems like a reasonable alternative and solution to reducing the overall impact of EOL scenarios. Additionally, considering alternative allocation procedures if the warehouse were to have other functions than simply storing and sorting PCC, the environmental benefits could be recoup at an even faster rate.

CHAPTER 6

LIFE CYCLE INVENTORY - MATERIALS

This chapter contains the impacts, environmental and economic, associated with all the materials that appear within the various EOL activities. This includes virgin and recycled content, pure and composite materials. Not all of the materials found in carpet are discussed in detail in this chapter, only those that play a significant role in the LCA are examined. The result of this chapter is the Material LCI that will be used to determine the impact assessments and comparative assessments of the EOL activities.

6.1 Polyvinylchloride

Polyvinylchloride (PVC) is the primary backing material of carpet-tiles. PVC is a costly material derived from crude oil and manufactured from processed chlorine, ethylene, hydrogen chlorine, dichloroethane -1, 2, and vinyl chloride. This chemical progression from crude oil to usable PVC is represented in Figure 6.1 (Realff *et al.*, 2004). The numbers in brackets indicate the amount, by weight unit, of each material needed to produce 1 weight unit of PVC. The background shade of each cell represents the level of chemical processing required for the particular material (i.e., white cells indicate natural, unprocessed resources and the black PVC cell indicates the final processed product derived as a combination of the materials preceding it in the tree). Additionally, the grayed cells with white writing indicate commodity chemicals. As this chemical tree supports, for every 1kg of PVC produced approximately 0.610kg of crude oil, 0.616kg of salt rock, 0.150kg of untreated water, and 0.166kg of air are needed for production. In other words, it takes 1.542kg of raw materials to produce 1kg of PVC. This is a material loss of approximately 35%.

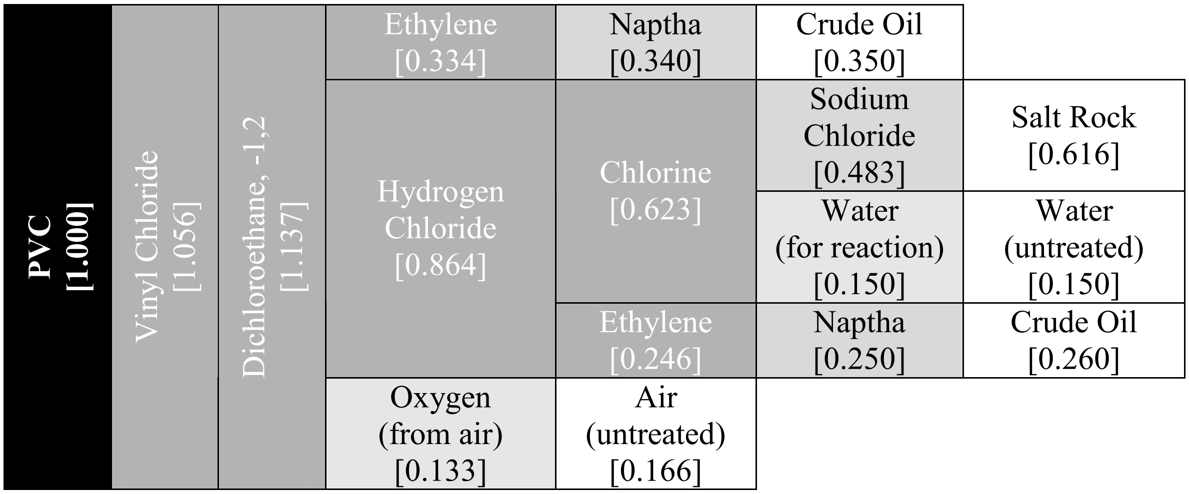


Figure 6.1: Polyvinylchloride Chemical Tree

In addition to the process chemicals needed to produce PVC, there are energy requirements needed to facilitate the transformations from raw materials to a usable PVC material. These energy requirements come in the form of electricity, steam, transport fuel and non-transport direct fuel use.

ENVIRNOMENTAL IMPACT:

Based on the raw material estimates in Figure 6.1 and the energy requirements necessary for producing PVC, I have calculated pollutant emissions estimates. This estimate is compared to environmental output estimates for PVC that can be found in generally accepted LCI databases such as IdeMat and NREL in order to determine the validity of the LCI for PVC (IdeMat, 2001) (NREL, 2007) (Realff *et al.*, 2004). This comparison is located in Table 6.1.

Table 6.1: Virgin PVC LCI Database Comparisons

	Greenhouse Gases [g-pollutant/kg-PVC]			**Criteria Pollutants** [g-pollutant/kg-PVC]				**Additional Pollutants** [g-pollutant/kg-PVC]				
Source	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
Energy Production Requirements	1654	0.0007	0.0007	5.87	2.98	N/R	5.78	N/R	0.00002	0.47	0.069	N/R
Raw Materials Requirements (Crude Oil)	285	0.02	0.00005	4.17	5.15	N/R	0.79	0.0015	N/R	0.61	0.021	0.026
Summary - Production	1940	0.023	0.0007	10.04	8.13	N/R	6.57	0.0015	0.00002	1.08	0.091	0.026
IdeMat soft PVC	2500	11	N/R	N/R	14	N/R	2.1	N/R	N/R	2.2	3.6	13
NREL PVC – Cradle to Resin	1820	13.5	0.042	14.2	3.27	0.00009	3.16	0.75	0.00004	0.32	0.71	10.5
Average	2087	8.17	0.02	12.12	8.47	0.00009	3.94	0.38	0.00003	1.20	1.47	7.84
Deviation	362.95	7.17	0.03	2.94	5.37		2.34	0.53	0.00001	0.95	1.87	6.88

It appears that the emissions estimates for CO_2 and SO_2 are in relative agreement with a standard deviation percentage below 25% for the various LCI databases. However, there are noticeable discrepancies, with a standard deviation percentage of over 75%, between each source with respect to CH_4, N_2O, VOCs, and PM emissions. Additionally, some of the datasets are incomplete and thus a fully comprehensive comparison between all LCI databases is not possible. Therefore, it is required that some assumptions be made in order to create a comprehensive LCI dataset to be used in this comparative LCA study in order to estimate the environmental impacts of PVC in each EOL scenario.

The first assumption addresses the incompleteness of the datasets. The blank fields in Table 6.1 correspond to the pollutants with the smallest emissions rate per kg-PVC. Pb and Hg emission rates appear to be negligible and thus were probably excluded from the IdeMat datasets due to their virtual insignificance. Additionally, there are no (or minimal) emission rates for the Energy-Material Summary-Production datasets in these categories due to the LCIs for GA Energy Production and Transportation used in this study and discussed in Chapter 4. Even though the emission rates for Pb and Hg are not complete for every LCI dataset considered, the study will assume that the impact in these two pollutant categories is represented by the average emission rates for each pollutant. Thus, for the purposes of this study, the emission rate for Pb is assumed to be 0.0001 g-Pb/kg-PVC and for Hg is 0.00003 g-Hg/kg-PVC.

The second set of assumptions made here reconciles the impacts of the pollutants whose standard deviation percentages exceed 75% of the average emission rate; this includes CH_4, N_2O, VOCs, PM, and SO_x. Starting with the CH_4 emission rate, the most prominent discrepancy is between the Energy-Material Summary-Production datasets and the IdeMat and NREL datasets. If the Energy-Material Summary-Production dataset is removed, the resulting average pollution rate for CH_4 is 10.27 g-CH_4/kg-PVC with a standard deviation of 3.66. The differences between the two average rates could be a result of the differences in representation of Electricity and Transportation impacts. In the Energy-Material Summary-Production dataset the LCIs for Electricity in Georgia and Transportation based on the assumptions made early is used for this particular study; thus, there are differences in the these impacts due in part to the localized assumptions made for this study as compared to the national averages used in the IdeMat and NREL datasets. Additionally, the distances used in the intermediate steps of PVC production probably vary between datasets which would cause greater discrepancies in the overall impacts. Thus, for the purposes of this study, the average pollution rate for CH_4 based on the IdeMat and NREL datasets will be used. It is a little more difficult reconciling the difference in emission rates for N_2O because the datasets are incomplete; IdeMat provides no N_2O output information for PVC production. Because there is no emission rate for N_2O in the IdeMat dataset, it will be assumed that the per kg-PVC pollution rate is nearly negligible. Therefore, the smaller emission rate will be used in this study. And, for the same reasoning as I have just discussed for N_2O, the smaller estimate for VOCs emissions will be used. Accurately capturing the PM emissions is a little more difficult. There is no agreement amongst any of the datasets regarding the pollution rate of PM. The standard deviations percentages are over 75% regardless of the dataset combination. Because of the lack of consensus, the overall average, factoring the IdeMat dataset into the average only once, will be used; thus, the resulting PM emission rate used in this study is 1.47 g-PM/kg-PVC. Lastly, the SO_x rates are reconciled by excluding the incomplete Energy-Material Summary-Production dataset from the average rate. This dataset is incomplete, due in part to the localized Electricity and Transportation assumptions used in this study to create the dataset, and drastically skews the average emission rate. Thus, the rate used in this study is 10.43 g-SO_x/kg-PVC.

The remaining pollutants' emission rates are in relative agreement amongst the various datasets. Therefore, the averages for NO_x, CO, and HC will be used in this study to represent the environmental impacts for these respective pollutants in the PVC production process. An environmental impact summary of the pollutant emissions rate for virgin PVC production is found in Table 6.2.

Table 6.2: Virgin PVC Pollution Emission Rates

Greenhouse Gases [g-pollutant/kg-PVC]			**Criteria Pollutants** [g-pollutant/kg-PVC]				**Additional Pollutants** [g-pollutant/kg-PVC]				
CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
2015	10.27	0.0007	12.12	8.43	0.0001	4.03	0.002	0.00003	1.40	1.47	10.43

ECONOMIC IMPACT:

In order to determine the economic impact of virgin PVC or the potential economic savings by recycling the PVC, it is necessary to assess the current market price of the PVC resin. According to Plastics Technology, the current PVC resin price for the copolymer flooring variety, including standard transportation by rail, is between 69¢ and 74¢ per lb-PVC ($1.52-$1.63/kg-PVC). A historical cost review, based on past reports by Plastics Technology, indicates a rise in the resin prices of about 10% since 2005. This is a yearly increase of around 3%. The rise and fall of the PVC market price is directly correlated to the fluctuation in the market price for the Ethylene Monomer (PTOnline, 2008). Thus, another way to track the prices of PVC is by studying the price of the

Ethylene Monomer, which itself is directly correlated to the market price of crude oil. Given the current price of crude oil and the rising market trends, it is safe to assume that the PVC market price will continue to rise at a steady rate proportional to that of crude oil. However, for this study, it will be assumed the market price of PVC to be the current average which is 72¢/lb-PVC or $1.59/kg-PVC.

The EOL scenarios that include PVC are the generic landfill scenario for PCC-tile and the consequential replacement of the landfilled PVC with virgin PVC and the PMR scenario which includes the collection of PCC-tile, the recapturing of the PVC from the backing and the pelletizing of the recycled PVC for reuse in carpet-tile backing.

6.2 Nylons

6.2.1 Nylon 6

Nylon 6 is a polymer derived from crude oil and refined to its monomer, caprolactam, which is then transformed with heat in the presence of Nitrogen into the Nylon 6 polymer chain. The Nylon 6 is then spun into fibers for use in both broadloom carpet and carpet tiles. Approximately 30% of all broadloom commercial carpets are comprised of Nylon 6 fibers and all of the carpet tiles, while 25% of the residential carpet market is Nylon 6 (Wang, 2006). Figure 6.2 contains the material inputs and transformations from crude oil to Nylon 6. Again, the background shade of each cell represents the level of chemical processing required for the particular material (i.e., white cells indicate natural, unprocessed resources and the black Nylon 6 cell indicates the final processed product derived as a combination of the materials preceding it in the tree). The grayed cells with white writing indicate commodity chemicals. As this chemical tree supports, for every 1kg of Nylon 6 produced approximately 0.798kg of crude oil, 0.200kg of untreated water, 0.100kg of sulfur, 0.041kg of natural gas, and 1.389kg of air are needed for production. In other words, it takes 2.528kg of raw materials to produce 1kg of PVC. This is a material loss by weight of approximately 60%.

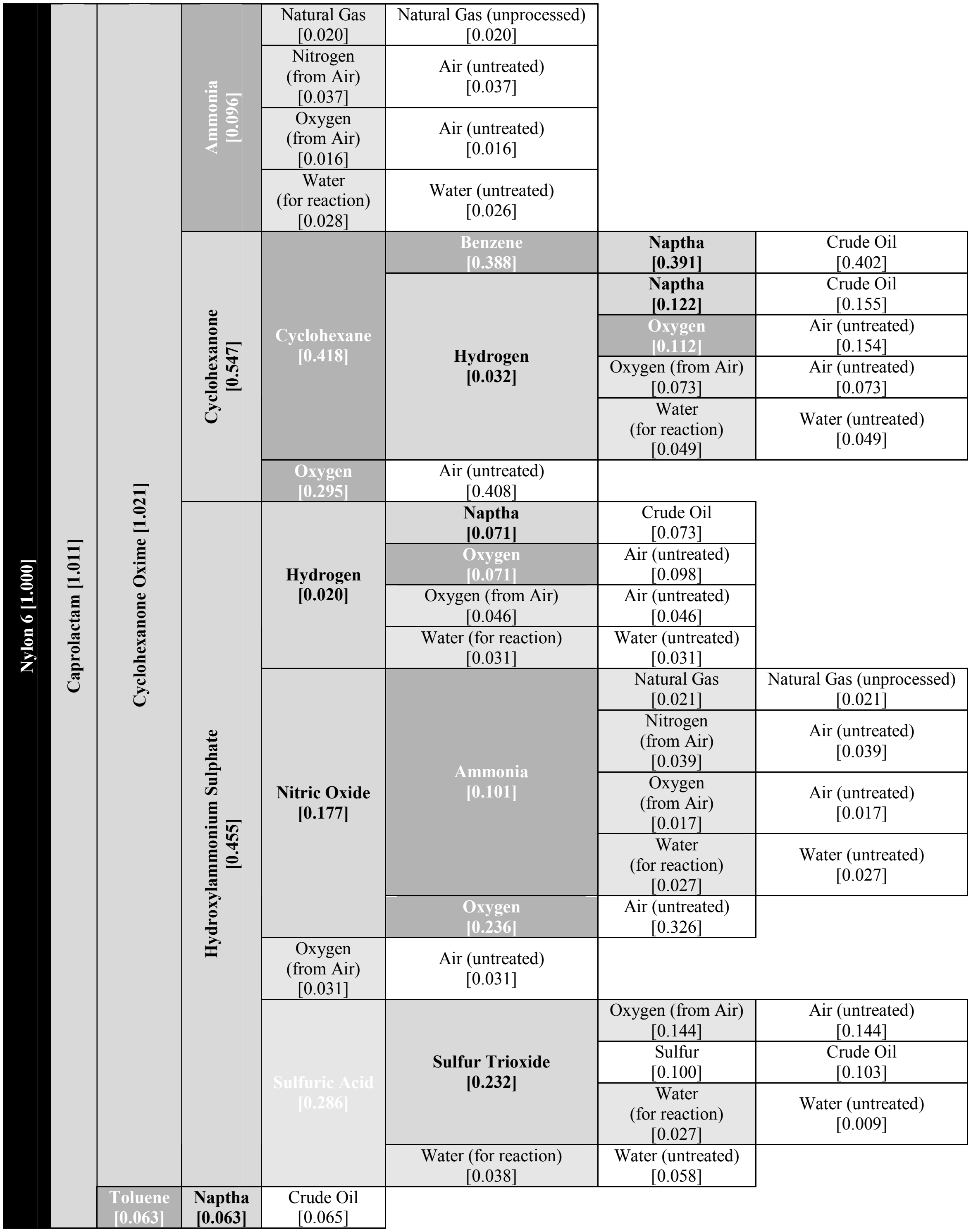


Figure 6.2: Nylon 6 Chemical Tree

In addition to the process chemicals needed to produce Nylon 6, there are energy requirements needed to facilitate the transformations from raw materials to a usable

Nylon 6 material. These energy requirements come in the form of electricity, steam, transport fuel and non-transport direct fuel use.

ENVIRONMENTAL IMPACT:

Based on the raw material estimates in Figure 6.2 and the energy requirements necessary for producing Nylon 6, the pollutant emissions estimates have been calculated. This estimate is compared to the environmental output estimates for Nylon 6 that are found in the generally accepted SimaPro7 dataset. The comparison is located in Table 6.3 (Consultants, 2007) (Realff *et al.*, 2004).

Table 6.3: Virgin Nylon 6 LCI Database Comparisons

	Greenhouse Gases [g-pollutant/kg-N6]			**Criteria Pollutants** [g-pollutant/kg-N6]				**Additional Pollutants** [g-pollutant/kg-N6]				
Source	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
Energy Production Requirements	1314	0.0007	0.0007	6.79	2.76	N/R	5.54	N/R	0.00002	0.46	0.04	N/R
Raw Materials Requirements (Crude Oil & Natural Gas)	286	0.02	0.00005	4.10	5.14	0.000001	0.79	0.001	0.0000001	0.66	0.03	0.04
Summary - Production	1599	0.02	0.0007	10.89	7.90	0.000001	6.33	0.001	0.00002	1.13	0.07	0.04
SimaPro7 – Nylon 6	5342	46.87	8.61	16.60	18.59	0.00001	9.74	0.02	0.00001	6.90	2.91	
Average	3471	23.45	4.30	13.75	13.25	0.000003	8.03	0.01	0.00004	4.01	1.49	0.04
Deviation	1323	16.56	3.04	2.02	3.78	0.000001	1.21	0.007	0.00002	2.04	1.00	

Between the two datasets, there are some discrepancies and some agreements between the various pollution rates. First, the SO_2 and CO rates are of the same magnitude for both estimates. However, there are several emission rates that are not even of the same magnitude between datasets. The CH_4 and N_2O emission rate averages have a standard deviation of 70%. Additionally, there is significant disagreement between the dataset emission rates for VOCs and PM. For these four pollutants, the Energy-Material Summary-Production estimates are all lower than the SimaPro7 estimates. The underestimates could be due to the localized nature of the transportation and electricity LCIs that are used in the study whereas the SimaPro7 dataset utilizes more widespread data. For the purposes of this study, the SimaPro7 dataset pollution estimates for these categories will be used because the more generalized nature of the database better supports the pollution estimates of a material that is not manufactured locally. However, for the remaining pollutants, not explicitly discussed here, the average rates will be used since there appears to be some relative agreement between the two estimates.

Table 6.4: Virgin Nylon 6 Pollution Emission Rates

Greenhouse Gases [g-pollutant/kg-N6]			**Criteria Pollutants** [g-pollutant/kg- N6]				**Additional Pollutants** [g-pollutant/kg- N6]				
CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
3471	46.87	8.61	13.75	13.25	0.000003	8.03	0.02	0.00004	4.01	1.49	0.04

ECONOMIC IMPACT:

In order to determine the economic impact of virgin Nylon 6, or the potential economic savings by recycling the material, it is necessary to assess the current market price of the virgin resin. According to Plastics Technology, the current Nylon resin price for the Nylon 6 variety is between $1.39 and $1.59 per lb-N6 ($3.06-$3.51/kg-N6). An historical cost review, based on past reports by Plastics Technology, The Innovation

Group, and Ides, indicates an annual rise in the resin prices of about 2.4% since 1997. (iIDES, 2008; Kirschner, 2008; PTOnline, 2008). Although the rising market trend does not appear to be waning, for this study it is assumed that the market price of Nylon 6 to be the current average which is \$1.49/lb-N6 or \$3.28/kg-N6. The price of the N6 monomer, caprolactam, also plays an important role in this study. Its market value is estimated at \$2.35/kg-caprolactam. This estimate is the 2007 average market price of the monomer on the US market (Fibre2Fashion, 2008).

The EOL scenarios that include Nylon 6 are the generic landfill scenario for both PCC-tile and PCC-broadloom and the consequential replacement of the landfilled Nylon 6 with virgin Nylon 6 and the PMR scenario which includes the collection of PCC-broadloom, the recapturing of the Nylon 6 from the face fibers and the chemical processing of the recaptured Nylon 6 back into the N6 monomer or Caprolactam.

6.2.2 Nylon 6,6

Nylon 6,6 is created in a reaction between a diamine and a dibasic acid, specifically Hyxamethylene Diamine and Adipic Acid. These two chemicals trace back to several main raw material inputs including air, bauxite, biomass (including water), dolomite, limestone, nitrogen, oxygen, rutile, sulfur, sand, and sodium chloride. Table 6.5 contains the amounts of these main components needed to produce 1 kg-N66.

Raw Material	[g-raw material/kg-N66]
Air	1700
Bauxite	3.50
Biomass (including water)	39.00
Dolomite	0.61
Limestone	3.20
N_2	170
O_2	0.35
Rutile	0.85
Sulfur	14.00
Sand	0.19
Sodium Chloride	29.00

Table 6.5: Raw Material Inputs for Nylon 6,6 Production

Overall the production of 1kg of N66 requires approximately 1961g of raw materials. This represents a material loss of nearly 50%. In addition to the material inputs, approximately 140MJ of energy are required for the production of 1kg-N66. This energy comes in the form of electricity (20%), oil fuels (29%), and miscellaneous fuels (51%) (Boustead, 2005).

ENVIRNOMENTAL IMPACT:

Based on these inputs, the environmental impacts in the form of pollution emission rates for the production of 1kg-N66 are summarized in Table 6.6. In order to check the validity of the pollution rates used, a comparison is set up amongst several publicly available LCI databases. SO_x emissions are not uniquely noted here, but are instead grouped with the SO_2 pollution rates. The three datasets represented, SimaPro7, IdeMat and Plastics*Europe* report on POLYAMIDE 66 (Nylon 66) are in relative agreement in most categories except N_2O and VOCs. For both of these pollutants, the IdeMat database is the outlier and will therefore not be included in the average environmental impact used in this study. Because of the near perfect agreement between these two datasets, the average pollution rates summarized in Table 6.7 will be used in order to asses the environmental impacts of Nylon 6,6 in the various EOL studies considered.

Table 6.6: Virgin Nylon 6,6 LCI Database Comparisons

	Greenhouse Gases [g-pollutant/kg-N6,6]			**Criteria Pollutants** [g-pollutant/kg-N6,6]				**Additional Pollutants** [g-pollutant/kg-N6,6]				
Source	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
*Plastics*Europe – *Nylon 6,6*	6500	49.00	0.74	18.00	14.00	0.00	7.30	0.02	0.00	4.23	2.10	N/R
SimaPro7 – Nylon 6,6	6542	49.26	0.74	17.81	13.54	0.000004	7.32	0.02	0.00001	4.20	2.13	N/R
IdeMat – PA 66	7000	28	15	29	26	N/R	4	0	N/R	3	N/R	N/R
Average	6681	42	5	22	18	0.000002	6	0.08	0.000004	4	2	N/R
Deviation	277	12	8	6	7	0.000003	2	0.10	0.00001	0.57	0.02	

Table 6.7: Virgin Nylon 6,6 Pollution Emission Rates

Greenhouse Gases [g-pollutant/kg-N66]			Criteria Pollutants [g-pollutant/kg-N66]				Additional Pollutants [g-pollutant/kg-N66]				
CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
6681	42.09	0.74	21.60	17.85	0.000002	6.27	0.08	0.000004	3.89	2.11	N/R

ECONOMIC IMPACT:

In order to determine the economic impact of virgin Nylon 6,6 or the potential economic savings by recycling the Nylon 6,6, it is necessary to assess the current market price of the resin. According to Plastics Technology, the current Nylon resin price for the 6,6 variety, is between $1.53 and $1.68 per lb-N66 ($3.37-$3.70/kg-N66). A historical cost review, based on past reports by Plastics Technology, indicates a relatively stable market price for virgin Nylon 6,6 (PTOnline, 2008). Thus, the market price of Nylon 6,6 is assumed to be the current average which is $1.61/lb-PVC or $3.55/kg-N66.

The EOL scenarios that include Nylon 6,6 are the generic landfill scenario for PCC and the consequential replacement of the landfilled Nylon 6,6 with virgin Nylon 6,6 and the SMR scenario which includes the collection of PCC, the recapturing of the Nylon 6,6 fibers from the backing and the pelletizing of the recaptured materials for use in extruded or compression molded plastics for the auto industry.

6.3 Glass Fiber Additives

ENVIRNOMENTAL IMPACT:

Glass fibers are included in the material LCI because they are a necessary additive for the SMR EOL scenario in which N66 is recycled into pelletized plastics for a second life use in molded auto parts. The glass fibers are added to reinforce the nylon pellets for a stronger and more durable plastic. The environmental impacts associated with the glass fibers are found in Table 6.8 and come from the IdeMat dataset for E-glass fibre (IdeMat, 2001).

Table 6.8: Virgin Glass Fiber Pollution Emission Rates

Greenhouse Gases [g-pollutant/kg-fibers]			Criteria Pollutants [g-pollutant/kg-fibers]				Additional Pollutants [g-pollutant/kg-fibers]				
CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
488.3	0.0001	N/R	0.01	3.024	0.003	0.008	N/R		0.011	0.44	2.27

ECONOMIC IMPACT:

In order to assess the economic impact of the glass fibers used to reinforce the Nylon 6,6 in the SMR-N66 EOL scenario, it is necessary to assess the current market price of the fiber. Unfortunately, there are no available prices for the glass fibers alone; therefore, the cost is determined to be the difference between the glass reinforced N66 and the N66 plain resin. According to Plastics Technology, the current Nylon resin price for the 6,6 variety, is between \$1.53 and \$1.68 per lb-N66 (\$3.37-\$3.70/kg-N66), and the price for the 30% glass reinforced N66 is \$1.42 and \$1.92 per lb-N66, 30% glass (\$3.13-\$4.23/kg-N66, 30% glass) (PTOnline, 2008). The average difference is around 14¢/kg-material, which will be used to represent the market price of glass fibers used to reinforce the N66 pellets.

The EOL scenario that includes glass fibers is the SMR-N66 scenario where N66 face fibers are captured and recycled into glass fiber reinforced plastic pellets to be used in the auto industry for molding. It will not be included in the generic landfill scenario used as the baseline for comparison. Instead, the landfill scenario will include the acquisition of virgin glass reinforced N66 materials as a composite material. Refer to Section 6.6 for more information on the composite glass reinforced N66 material.

6.4 Nylon Broadloom Carpet

Nylon broadloom carpet here refers to carpet as one virgin material. Thus, the LCI database for this particular material will not isolate the individual materials, but will instead provide the data necessary for the composite assessment. The data for nylon broadloom carpet was retrieved from the BEES database for the Generic Nylon Carpet: Broadloom Carpet: Standard Glue category. The assumptions for this material fall under the following categories: generic broadloom carpet material composition, manufacturing requirements, installation, use, and disposal (NIST, 2007). Each of these assumptions will be explored, modifying or justifying them according to the Scope and Bounds of this study. First, the assumptions of the material carpet composition by weight are outlined in Table 6.9.

Table 6.9: Generic Nylon Broadloom Carpet Composition

Material	g/m^2	%composition
Nylon	1,029	42.34%
Polypropylene	227	9.34%
Styrene Butadiene Latex	263	10.82%
Calcium Carbonate Filler	909	37.40%
Stainblocker	0.24	0.01%
Other Additives	2	0.08%
TOTAL	**2430.24**	

This assumption jives with the broadloom carpet composition assumptions of this study discussed in Section 2.2.3 and outlined Table 2.2: Broadloom Material Composition.

The manufacturing assumptions assumed in BEES are broken down into Energy Requirements, Emissions, Solid Wastes, and Transportation sub categories. The Energy Requirements refer to the energy demands of the individual unit processes, including steps such as formation of fibers, dyeing, tufting, etc. These energy requirements are translated into emissions based on national emission estimates for electricity and fuel combustion. This assumption, although not of the preferred Localized Data specificity, does offer a reasonable dataset for emissions based on energy requirements and manufacturing processes. The Solid Wastes category assumes that there is a cumulative material loss of 9% throughout the manufacturing process. This appears to be a reasonable loss assessment and thus will remain unchanged. The Transportation category refers to the transportation of materials between the various intermediate processing sites. The assumption here is a raw materials transport of 250miles (402km) by truck. This is a uniform industrial average and thus will remain unchanged.

The impacts of the Installation and Use phases of the carpet manufacturing process are included in the aggregated final output impacts of the BEES dataset. As defined in the Scope and Bounds of this study, the Installation and Use phases in the overall Life Cycle Impact Assessment will not be considered here; thus, these assumptions are not valid and therefore must be amended. However, in looking at the individual environmental impacts associated with the various Life Cycle Stages in BEES, the Installation and Use phases barely register in the various impact categories. The impact is dominated by the Raw Material Acquisition phase in all impact categories except VOCs, which is only a result of the Use phase. Thus all impacts will be left as they appear in the BEES dataset, with the exception of the VOCs category, which is zero for the life cycle phases considered in this study because it is only a product of the Use phase which is not included in this study which begins the assessment from waste generation.

The BEES dataset also contains the impacts of the EOL phase. The assumption here is a 0.7% recycling rate. Since this study is designed to assess the EOL options for PCC, the impacts of this particular life cycle phase should not be included. However, after examining the overall impacts of the individual life cycle phases, the EOL phase does not even register an impact; thus the BEES dataset will be left as is with regards to the EOL life cycle phase.

ENVIRNOMENTAL IMPACT:

Based on the assumptions discussed here, the following table, Table 6.10, includes an outline of the impacts associated with nylon broadloom carpet as a material in itself.

Table 6.10: Virgin Nylon Broadloom Carpet Emission Rates

Greenhouse Gases [g-pollutant/kg Broadloom]			**Criteria Pollutants** [g-pollutant/kg Broadloom]				**Additional Pollutants** [g-pollutant/kg Broadloom]				
CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
5316	19.70	0.41	25.95	19.69	0	5.70	0	0.00005	3.08	5.63	N/R

ECONOMIC IMPACT:

Lastly, it is necessary to determine the market price of nylon broadloom carpet in order to provide a basis for economic comparisons. An average of Nylon Broadloom carpet products from retailers such as Home Depot and Lowe's (available online) comparably compares to the estimated price used by the BEES database. This price is around \$7.94/m^2. Multiplying this price by the average density of broadloom carpet, the resulting market price per kilogram broadloom carpet is \$3.61. This price will be used to assess the economic impacts associated with the production of new nylon broadloom carpet.

6.5 Carpet Underlay

Carpet underlay refers to carpet padding or cushion that goes under broadloom carpet to increase a carpets life, muffle noise, and provide cushioning for increased comfort. For this study, the carpet underlay will be considered as one virgin material with an impact based on the current industry averages for material composition and manufacturing practices. Thus, the LCI database for this particular material will not isolate the individual materials, but will instead provide the data necessary for the composite assessment. The data for carpet underlay was retrieved from the BEES database for cushion rolls manufactured by Collins and Aikman (C&A) for their ER3 RS and Ethos RS models. The material composition of these two carpet pads is found in Table 6.11 and their corresponding environmental data is located in Table 6.12. The assumptions for this material fall under the following categories: composition, manufacturing requirements, installation, use, and disposal (NIST, 2007). Each of these assumptions will be explored, modifying or justifying them according to the Scope and Bounds of this study.

The manufacturing assumptions assumed in BEES are broken down into Raw Materials, Energy Requirements, Emissions, and Transportation sub categories. The Energy Requirements refer to the energy demands of the individual unit processes, including steps such as the dying of yarn, manufacturing the underlay, etc. These energy requirements are translated into emissions based on national emission estimates broken down as follows: 27% electricity, 59% natural gas, 12% fuel oil, and 2% biodiesel. These assumptions, although not of the preferred Localized Data specificity, do offer a reasonable dataset for emissions based on energy requirements and manufacturing processes. The Transportation category refers to the transportation of materials between the various intermediate processing and is a representation of industrial averages and thus will remain unchanged.

The various life cycle phases included in the LCI are Raw Material Acquisition, Manufacturing, Installation, Use and End of Life. As defined in the Scope and Bounds of this study, the Installation and Use phases will not be included in the overall Life Cycle Impact Assessment; thus, these assumptions are not valid and therefore must be amended. However, in looking at the individual environmental impacts associated with the various life cycle stages in BEES, the Installation and Use phases barely register in the various impact categories. The impact is dominated by the Raw Material Acquisition phase and Manufacturing in all impact categories except VOCs, which is only a result of the Use phase. Thus, all impacts will be left as they appear in the BEES dataset, with the exception of the VOCs category, which is assumed to be zero for the life cycle phases considered in this study. The BEES dataset also contains the impacts of the EOL phase. The assumption here is that all of the material can be recycled in a closed-loop process. Since this particular study is designed to assess the EOL options for PCC, the impacts of this particular life cycle phase should not be included. However, after examining the overall impacts of the individual life cycle phases, the EOL phase does not even register an impact in any of the categories; thus, the BEES dataset will be left as is with regards to the EOL life cycle phase. The overall LCI for environmental impact that is used in this study is outlined in Table 6.12 under the "Average" Product category.

Table 6.11: Carpet Underlay Material Composition

Material	% Composition by Weight
Nylon 6,6 Yarn	2.5%
Post-Industrial Nylon 6,6	14%
Primary Backing	4%
Recycled-Content Filler	63.5%
Other Additives	16%

ENVIRNOMENTAL IMPACT:

Table 6.12: Carpet Underlay Emission Rates

	Greenhouse Gases [g-pollutant per kg-underlay]			Criteria Pollutants [g-pollutant per kg-underlay]				Additional Pollutants [g-pollutant per kg-underlay]				
Product	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
ER3 RS	779	3	0.024	5.60	2.44	0	1.46	0	0.00001	0.97	0.98	N/R
Ethos RS	948	3.83	0.024	7.12	2.67	0	2.44	0	0.00002	0.97	0.56	N/R
Average	864	3.414	0.024	6.36	2.55	0	1.95	0	0.00001	0.97	0.77	N/R

ECONOMIC IMPACT:

Lastly, it is necessary to determine the market price of the underlay in order to provide a basis for economic comparisons. An average of the two underlay types according to the BEES database is around \$3.17/m^2. Multiplying this price by the average density of the underlay, which is around 3.4kg/m^2, the resulting market price per kilogram carpet underlay is \$0.95. This price will be used to assess the economic impacts associated with the production of recycled PCC-broadloom content carpet underlay.

6.6 Glass Fiber Reinforced Plastic Pellets

Glass fiber reinforced plastic pellets are included in the LCI database because of their role in the SMR-N66 comparative assessment. In the SMR scenario, N66 is transformed into glass reinforced plastic pellets which are sold to the auto industry for use in plastic molded car parts. The composite material, although not incorporated into the individual impact assessment of the SMR-N66 scenario, it is included in the comparative assessment as it appears as the virgin material acquired in the baseline landfill scenario. The impacts associated with the published composite materials, and not a compilation of the N66 and glass fiber additives LCI dataset that was compiled for this study will be used, because a direct aggregation of these two dataset would not capture the energy required to create the reinforced plastic materials.

ENVIRONMENTAL IMPACT:

Two publicly available datasets, SimaPro and IdeMat, are used to estimate the impacts of this material at 30% glass fiber composition. The pollution rates are presented in Table 6.13. SO_x emissions are not uniquely noted here, but are instead grouped with the SO_2 pollution rates. Both datasets are in relative agreement in most categories except N_2O, VOCs, and PM. In order to reconcile these differences, individual dataset for N6,6 and glass fibers were referenced. In the case of N_2O, N6,6 has a pollution rate of 0.74g/kg-N66 while the glass fibers dataset has a rate of 3.024g/kg-fiber. Because of the higher glass fiber pollution rate, the average N_2O pollution rate for the composite material will be used because it is higher than the individual glass fiber pollution rate while not quite as high as the upper estimate found in the IdeMat database. In the case of the VOCs, only the N6,6 material has a reported pollution rage estimated at 0.08g/kg-N6,6. Because this number is near the average data point for the fiber reinforced plastic, the average pollution rate of the two databases will be used to estimate the VOCs rate of the glass reinforced plastics in this study. Lastly, the PM pollution rate is around 2.11g/kg-N6,6 and 0.44g/kg-fiber. These numbers are rather low and are closer, without going over, the estimated rate found in the SimPro database; therefore, the PM pollution rate provided by the SimaPro database will be used to estimate the PM emission for the fiber reinforced N6,6 in this study. For a complete environmental impact dataset used in this study is found in Table 6.14.

Table 6.13: Glass Reinforced Nylon 6,6 LCI Database Comparisons

	Greenhouse Gases [g-pollutant/kg-N66,GF30]			**Criteria Pollutants** [g-pollutant/kg-N66,GF30]				**Additional Pollutants** [g-pollutant/kg-N66,GF30]				
Source	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
SimaPro7 – N 6,6/glass fibre composite	6023	30	0.67	16	11	0.0000003	6.02	0.01	0.00001	3.31	3.40	N/R
IdeMat – PA 66 GF30	6500	26	13	29	29	N/R	2.30	0.20	N/R	2.52	11.00	N/R
Average	6261	28.07	6.83	22.72	20.01	0.000003	4.16	0.11	0.00001	2.92	7.20	N/R
Deviation	338	2.92	8.72	8.88	12.71		2.63	0.13		0.56	5.37	

Table 6.14: Glass Reinforced Nylon 6,6 Pollution Emission Rates

Greenhouse Gases [g-pollutant/kg- N66,GF30]			Criteria Pollutants [g-pollutant/kg- N66,GF30]				Additional Pollutants [g-pollutant/kg- N66,GF30]				
CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
6261	28.07	6.83	22.72	20.01	0.000003	4.16	0.11	0.00001	2.92	3.40	N/R

ECONOMIC IMPACT:

In order to determine the economic impact of virgin glass reinforced N66, or the potential economic gains resulting from recycling Nylon 6,6 face fibers into these plastic pellets, it is necessary to assess the current market price of the reinforced plastic. According to Plastics Technology, the current Nylon resin price for the 6,6 variety that is 30% glass reinforced,, is between \$1.42 and \$1.92 per lb-N66,GF30 (\$3.13-\$4.23/kg-N66,GF30). A historical cost review, based on past reports by Plastics Technology, indicates a relatively stable market price for the material (PTOnline, 2008). Thus, the market price of glass reinforced Nylon 6,6 is assumed to be the current average which is \$1.67/lb-N66,GF30 or \$3.68/kg-N66GF30.

The EOL scenario that includes glass reinforced Nylon 6,6 is the generic landfill scenario for PCC to be assess against the SMR-N66 EOL scenario. It is included in the landfill scenario at a rate of 1.42 the landfilled Nylon 6,6 that could have been recaptured from the PCC-broadloom.

6.7 Material Summary

Based on all of the material discussed previously in this chapter, Table 6.15 contains the LCI dataset for all of the materials used in this study. It includes both the economic and environmental impacts of the virgin, recycled, pure and composite materials that appear in the EOL scenarios assessed in Chapters 8 and 9.

		Greenhouse Gases [g-pollutant/kg-material]			**Criteria Pollutants** [g-pollutant/kg- material]				**Additional Pollutants** [g-pollutant/kg- material]				
Material	**[$/kg-material]**	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SO_x**
PVC	1.59	2015	10.27	0.0007	12.12	8.43	0.0001	4.03	0.002	0.00003	1.40	1.47	10.43
N6	3.28	3471	46.87	8.61	13.75	13.25	0.000003	8.03	0.02	0.00004	4.01	1.49	0.04
N66	3.55	6681	42.09	0.74	21.60	17.85	0.000002	6.27	0.08	0.000004	3.89	2.11	N/R
Glass Fibers	0.14	488	0.0001	N/R	0.01	3.024	0.003	0.008	N/R	N/R	0.011	0.44	2.27
Nylon Bloom	3.61	5316	19.70	0.41	25.95	19.69	0	5.70	0	0.00005	3.08	5.63	N/R
Underlay	0.95	864	3.414	0.024	6.36	2.55	0	1.95	0	0.00001	0.97	0.77	N/R
N66 GF30	3.68	6261	28.07	6.83	22.72	20.01	0.000003	4.16	0.11	0.00001	2.92	3.40	N/R

Table 6.15: Material Summary - Economic and Environmental Impact Datasets

CHAPTER 7

LIFE CYCLE INVENTORY – MECHANICAL AND CHEMCIAL UNIT PROCESSES

There are many ways to process PCC once it is collected. These processes can be mechanical, chemical or a combination of the two. For this study, each process is modeled independently so that TBL impacts can be realized for each unit process separately and for any combination of processes that might make up a given scenario. Additionally, each process is modeled as a stand-alone operation. In other words, no consideration is given to the impact of one process efficiency by upstream process efficiencies. Thus, the labor requirements are only those required by actual machine running time in which carpet is being processed. By considering each unit process, the drains of a particular EOL system can be more easily noticed thus providing greater insight into the impacts on the TBL of each activity included in the EOL scenario.

The remaining sections of this chapter discuss the mechanical and chemical processes individually. Each process is described and machine or chemical requirements are explained based on specific machine specifications, namely horsepower and throughput rates, or processes procedures, including any chemical reagents and energy requirements. These specifications and procedures are then translated into environmental impacts in the form of g-pollutant/kg-material processed, social impacts on a hours-labor/kg-material processed and \$-paid/kg-material processed, and economic impact on a \$/kg-material processed which takes into account money paid for utilities, material and labor. Additionally, for the processes that require energy in the form of electricity, a kWh/kg-material processed indicator will also be noted.

7.1 Life Cycle Inventory Calculation Methods

In this section the methods used to create the LCI database for this study are discussed. Each of the common methods has been isolated for calculating impacts across the three impact categories that will be applied to a variety of individual unit processes.

7.1.1 Electricity Consumption

These energy requirements for the mechanical processes are calculated from the machine specifications for horsepower and throughput rates. The equation used for this translation from machine specifications to energy requirements is found below (MnTAP, 2003).

$$M_i \times 0.746\left[\frac{kW}{hp}\right] \times \frac{1}{T_i} \times LF \times \frac{1}{eff}$$ **Equation 6**

Variable:	Description:	Unit:
M_i	machine specified horsepower for process *i*	hp
0.746	conversion factor	kW/hp
T_i	throughput rate for process *i*	kg/hr
LF	load factor – percent hp dedicated to process	
eff	motor efficiency	

As a baseline in this study, a LF of one and a motor efficiency of 100% will be assumed for all processes. However, some sensitivity to this factor will be explored in the comparative assessment conducted in Chapter 9. This, although not actually achievable in reality, will represent a lower bound or best case scenario for energy consumption rates per process. In other words, in reality the actual energy consumption rates, and thus pollutant emissions rates, would be higher than the rates expressed in this study. For a summary of the variable values used for the processes involved in this study, refer to Table 7.16 in Section 7.12.1.

7.1.2 Chemical Process Life Cycle Inventory Calculations

The chemical processes will be described according to their individual process procedure. Thus, impacts for these processes will include not only the energy required for the chemical transformation, but also any chemical or material reagents and solutions that facilitate the reactions. Therefore, the impact from the energy requirements will be based on the electricity grid in Georgia, outlined in Chapter 4, and the impact of manufacturing the chemicals necessary based on data obtained from existing LCI databases.

7.1.3 Social Impact Life Cycle Inventory Methods

The social impact inventories for each of the processes are determined by both potential employment opportunities and salaries paid. The functional units for these two categories are employment-time [hr or min] per kg-material and salary costs [$ or ¢] per kg-material. The impacts are directly related to the process inputs of throughput rates and labor requirements. Thus, in each process description the number of employees required for the process will be included. As a general rule, processes that involve cutting components will require two employees per process for safety reasons and all other processes will require only one employee. The wage rates will vary somewhat by a particular process. These estimates will be based on national, metropolitan level, or census region data provided by the BLS for the occupational group that most closely correlates to the particular process being described. Data for the Atlanta-Sandy Springs-

Marietta Metropolitan Region will be used when available. However, the nationally aggregated wage estimates, specifically for the Textile Mills industrial category, should still accurately reflect the wage rates of the carpet industry in Georgia given that the vast majority of the industry is concentrated within the state. Additionally, it is important to note that the average wage rate of all employees in the carpet industry, based on CRI statistical estimates, is approximately $13.39 per hour (Braun and Peoples, 2003). In order to verify the wage estimates of the BLS, the degree of agreement between the particular wage rates of the BLS and the CRI wage estimate will be assessed.

7.2 Baling

Baling is the mechanical process in which loose material is compressed into bundles in order to minimize the space the material occupies during storage and transportation. The IPS Conquest Series Balers, recommended by C.A.R.E. for carpet recycling, are considered in this study. The machine and performance specifications for the vertical Conquest 180-100S HI GRADE material equipment are used to estimate the energy requirements and throughput rates of the baling processes within each of the EOL scenarios. The average machine specifications for the various balers are 108hp motor and a throughput rate of 38,100kg/hr. This translates to a minimum electric pull of 0.002 kWh/kg-material baled (IPS, 2007). The wage rates for this particular process are based on the average rates of the *Warehousing and Storage: Transportation and Material Moving Occupations: Machine Feeders and Offbearers* (SOC code: 53-7063), which is defined by those jobs that require the feeding and removing of materials from automated equipment. There is localized data for this particular occupational category that is averaged for Dalton, GA. Thus, the average hourly rate for this occupational category, which will be used for the baling process, is \$11.80 with a relative standard error of 3.0% (BLS, 2007). Based on these labor and energy requirements and the average throughput rate for the baling process, the various impacts can be found in Table 7.1.

Table 7.1: Baling Requirements per Kilogram-Processed Material

kWh	g-CO_2	g-SO_2	g-NO_x	g-Hg	# laborers	min/laborer	¢-labor	¢-energy
0.002	1.33	0.009	0.002	0.00000003	1	0.002	0.03	0.01

7.3 Shredding

Shredding is the mechanical process of reducing the size of material from bales or loose whole carpet to shreds of material ranging in size from 2" to 4". Energy and throughput estimates are determined by averaging performance and machine specification of several C.A.R.E recommended machines. Based on these machine specifications the average motor requirements are 269hp with a throughput rate of 3580kg/hr (Overcash, 2006). This translates to a minimum electric pull for the shredding processes of 0.056kWh/kg-recyclable material shredded. The wage rates for this particular process are based on the national statistics for *Textile Cutting Machine Setters, Operators, and Tenders* (SOC code: 51-6062), with a job description of setting up, operating, and tending machines that cut textiles, is estimated at \$13.21 per hour with a relative standard error of 7.4% (BLS, 2007). Based on this data, the process emission rates and social and economic impacts can be found in Table 7.2.

Table 7.2: Shredding Requirements per Kilogram-Processed Material

kWh	g-CO_2	g-SO_2	g-NO_x	g-Hg	# laborers	min/laborer	¢-labor	¢-energy
0.056	35.34	0.23	0.043	0.0000007	2	0.017	0.74	0.31

7.4 Grinding

The grinding process is another mechanical size reduction process where the material shreds averaging around 2.5" in size are further reduced to material pieces averaging around 3/8" in size. The summarized machine and performance specifications of the HiTorc Grizzly material grinder, which is used in this study to represent the social, economic, and environmental inputs and outputs of the grinding process within the material reclamation scenario, are a motor requirement of 200hp and a throughput rate averaging 2,720kg/hr (Overcash, 2006). This corresponds to a minimum process electricity requirement of 0.055kWh/kg-recyclable material grinded. Again, based on the wages estimates for the *Textile Cutting Machine Setters, Operators, and Tenders* occupational series (SOC code: 51-6062), an hourly rate of $13.21 with a relative standard error of 7.4% will be assumed (BLS, 2007). Based on this data, the process emission rates and other impacts can be found in Table 7.3.

Table 7.3: Grinding Requirements per Kilogram-Recyclable Material

kWh	g-CO_2	g-SO_2	g-NO_x	g-Hg	# laborers	min/laborer	¢-labor	¢-energy
0.055	34.58	0.23	0.042	0.0000007	2	0.022	1.00	0.31

7.5 Material Separation - Centrifuge

The Bird Humboldt Censor Three-Phase Centrifuge, which utilizes the CENSOR™ Centrifuge Technology, developed by the Bird Machine Company of Massachusetts, is recommended for highly selective material separation by density for granulated carpet particles. The energy requirements of the Bird Humboldt Censor Three-Phase Centrifuge are determined from the machine and performance specifications obtained from a CENSOR™ Centrifuge distribution representative. It will be assumed in this study that the separation is 100% effective thus representing an upper bound of material reclamation per material processed. The machine specifications for the centrifuge include a 363hp motor and a separation throughput rate of approximately 2000kg/hr (Roth, 2002). To estimate the labor wages of this process the metropolitan region estimates for the Separating, Filtering, Clarifying, Precipitating, and Still Machine Setters, Operators, and Tenders (SOC code: 51-9012) will be used, which has an hourly rate of $14.98 with a relative standard error of 9.5%. This particular job includes the use of centrifuges (BLS, 2007). Table 7.4 contains the corresponding impacts for the material separation process.

Table 7.4: Centrifuge Requirements per Kilogram-Recyclable Material

kWh	g-CO_2	g-SO_2	g-NO_x	g-Hg	# laborers	min/laborer	¢-labor	¢-energy
0.237	149.55	0.98	0.183	0.000003	1	0.03	0.75	1.33

7.6 Pelletizing

The pelletizing process mechanically compresses the collected material granules into pellets, which increases the ease with which they are handled and creates a more uniform melt during its second use in a compression mold, extrusion mold, or backing-material melt application. The entire process is comprised of three distinct phases. The first step is the pelletizing section, which includes a heater, to aid in material flow, and a cutter. The second section is a slurry circulation process that transports the pellets to the dryer. The last part of the process is the dryer, which is likely to be a centrifugal impact system. The overall specifications for the palletizing process include a collective horsepower of 460 and an average throughput rate of 18000kg/hr (Overcash, 2006). For this process, the wage requirements are estimated based on the *Textile Winding, Twisting, and Drawing Out Machine Setter, Operators, and Tenders* (SOC code: 51-6064) statistics. This job is defined by the setting up and operating of machines designed to draw out and combine textiles such as synthetic fibers, and the average hourly rate is $13.78 with a relative standard error of 4.1% (BLS, 2007). Table 7.5 contains the impacts of the palletizing process based on the machine specifications described above.

Table 7.5: Pelletizing Requirements per Kilogram-Processed Material

kWh	g-CO_2	g-SO_2	g-NO_x	g-Hg	# laborers	min/laborer	¢-labor	¢-energy
0.019	12.02	0.08	0.015	0.0000002	1	0.003	0.08	0.11

7.7 Card

Carding is the pre-process for needlepunching in which the center fabric through which the materials will be punched is manufactured. The card provides the structural stability for the needlepunched material. The wage requirements for this process are based on the *Textile Product Mills: Production Operations: Textile Knitting and Weaving Machine Setters, Operators, and Tenders (SEC code: 51-6063)* statistics for the Atlanta-Sandy Spring-Marietta metropolitan region of Georgia. This job is defined by the setting up and operating of machines designed to knit, loop, weave or draw textiles, and the average hourly rate is $13.08 with a relative standard error of 1.1% (BLS, 2007). Table 7.6 contains the impacts of the carding process based on the process specifications described above (Subbiah *et al.*, 2008).

Table 7.6: Carding Requirements per Kilogram-Processed Material

kWh	g-CO_2	g-SO_2	g-NO_x	g-Hg	# laborers	min/laborer	¢-labor	¢-energy
0.272	171	1.12	0.209	0.000003	1	0.109	2.38	1.52

7.8 Needlepunch

The needlepunch process mechanically forces material through a center carded material using barbed felting needles. For this study, the needlepunch process will be isolated to the manufacturing of carpet underlay or carpet padding; therefore the process specifications will be specific to this type of production. The process is run on a needlepunch machine which averages a motor horsepower of 200. This estimate is based on machine specifications described by a sales representative of the Dilo DI-LOOM OUGII S 25 needlepunch machine (DILO, 2008). Additionally, using the production specifications outlined by the Shoou Shyng Machinery Co., Ltd. for their needlepunch machine, a needling density of 1-6m/min has been assumed (allproducts.com, 2008). This roughly translates to a throughput rate of 1778kg/hr based on the CRI recommended carpet underlay density of 6lb/ft^3 (96kg/m^3) and thickness between ¼" and $^7/_{16}$" (0.011m-0.0064m) (CRI, 2007). The wage requirements are estimated based on the *Textile Product Mills: Production Operations: Textile Knitting and Weaving Machine Setters, Operators, and Tenders (SEC code: 51-6063)* statistics for the Atlanta-Sandy Springs-Marietta metropolitan region of Georgia. This job is defined by the setting up and operating of machines designed to knit, loop, weave or draw textiles, and the average hourly rate is \$13.08 with a relative standard error of 1.1% (BLS, 2007). Table 7.5 contains the impacts of the needlepunch process based on the machine specifications described above.

Table 7.7: Needlepunch Requirements per Kilogram-Processed Material

kWh	g-CO_2	g-SO_2	g-NO_x	g-Hg	# laborers	min/laborer	¢-labor	¢-energy
0.084	52.91	0.35	0.065	0.000001	1	0.034	0.74	0.47

7.9 Nylon Depolymerization

The nylon depolymerization process transforms the recaptured Nylon 6 face fibers into its monomer, caprolactam. This is done in a reactor under high heat and pressure with the presence of a catalyst. It reactor superheats the depolymerization environment to 250-400^{o}C and 1-100atm. This pressurization operates with about 500hp and a throughput rate of 4536kg-material processed per hour, which translates to roughly an energy pull of approximately 0.08kWh/kg-material processed. The impacts associated with the reactor along are presented in Table 7.9. The catalysts that initiate the chemical reaction can either be an acid or a base; for this study, NaOH will be used to approximate the impact of the catalyst in the reaction. The environmental and economic impacts of this catalyst are presented in Table 7.8. The concentration of nylon material to the NaOH catalyst is around 9:1 for the reaction. The depolymerization process itself runs at about an 80% yield (Subbiah *et al.*, 2008). The employment potential represented by the depolymerization process is based on the throughput rate and the average hourly wage of the *Chemical Equipment Operators and Tenders* (SOC code: 51-9011) which runs around $19.75/hr with a relative standard error of 7.9% (BLS, 2007). The LCI dataset for this entire depolymerization process is presented in Table 7.10.

Table 7.8: NaOH Economic and Environmental Impacts

Market Price	Greenhouse Gases [g-pollutant/kg-NaOH]			Criteria Pollutants [g-pollutant/kg- NaOH]				Additional Pollutants [g-pollutant/kg- NaOH]				
[$/kg-NaOH]	CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
3.70	1122	12	0.00000000001	4.82	3.01	0.000002	0.91	0.00004	0.0002	0.64	0.52	N/R

Table 7.9: Reactor Requirements per Kilogram-Processed Material

kWh	g-CO_2	g-SO_2	g-NO_x	g-Hg	# laborers	min/laborer	¢-labor	¢-energy
0.082	52	0.34	0.06	0.000001	1	0.013	0.44	0.46

Table 7.10: Depolymerization Requirements per Kilogram-Processed Material – Environmental

kWh	g-CO_2	g-CH_4	g-N_2O	g-SO_2	g-NO_x	g-Pb	g-CO	g-VOCs	g-Hg	g-HC	g-PM	g-SO_x
0.082	1174	12	0.00	5.16	3.07	0.000001	0.91	0.00004	0.0002	0.64	0.52	N/R

Table 7.11: Depolymerization Requirements per Kilogram-Processed Material – Social and Economic

# laborer	min/ laborer	¢-labor	¢-energy	¢-materials
1	0.013	0.44	0.46	41.11

7.10 Dryer

The drying process is used in the PMR-N6 depolymerization scenario. The industrial dryer uses 150hp to dry the separated N6 monomer post-depolymerization so that it can be used or sold as new material. The throughput rate of the dryer is roughly 4536kg-material processed per hour (Subbiah *et al.*, 2008). Again, to estimate the employment wage potential for this process, the average hourly wage of the *Chemical Equipment Operators and Tenders* (SOC code: 51-9011), which runs around $19.75/hr with a relative standard error of 7.9%, have been used (BLS, 2007). The impacts of the drying process are summarized in Table 7.12.

Table 7.12: Dryer Requirements per Kilogram-Processed Material

kWh	g-CO_2	g-SO_2	g-NO_x	g-Hg	# laborers	min/laborer	¢-labor	¢-energy
0.025	16	0.10	0.02	0.0000003	1	0.013	0.44	0.15

7.11 Cleaning Process

A dry carpet cleaning process involves cleaning agents and vacuums but does not require any water which eliminates the burdens associated with wastewater treatment and the increased energy for drying the moistened carpet. The dry cleaning model used here to represent the cleaning process of soiled carpet for a second life under the RMR EOL scenario is based on the BEES4.0 database under Building Maintenance: Cleaning Products: Carpet Cleaners. The specific product considered is the Racine Industries HOST Dry Carpet Cleaning System. This particular solvent uses a Green Seal®-certified, bio-based cleaning agent and a mixture of water and recycled organic fibers. The product works by mechanically brushing the solvent into the soiled carpet and then vacuuming the cleaning agent and dirt leaving a cleaner, healthier carpet for continued use.

The composition of the HOST cleaning agent is 0.015g-sanitizer/kg-HOST and 0.0076L-water/kg-HOST (7.6g-water/kg-HOST). By weight, the solvent is 63% water, 31% organic fibers, and 6% other materials. The BEES database provides some estimates for environmental impact, based on production of the product and its use. It is assumed that 4.25kg-HOST are needed to clean 92.9m^2-carpet (NIST, 2007). Using the functional unit established in this study, and assuming an average carpet weight of 2.7kg/m^2, this translates to 16.94g-HOST/kg-carpet. Table 7.13 contains the pollution rates per kg-HOST solvent used, and Table 7.14 translates these rates to the functional unit of g-pollutant/kg-PCC. (NOTE: The SO_x category is not explicitly defined in the BEES database; it is lumped into the SO_2 pollution rate.)

Table 7.13: Pollution Rates per kg-HOST

Greenhouse Gases [g-pollutant/kg-HOST]			Criteria Pollutants [g-pollutant/kg-HOST]				Additional Pollutants [g-pollutant/kg-HOST]				
CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
6112	15.89	0.01	47.67	7.43	0.00	3.67	14.71	0.0001	1.30	4.57	N/R

Table 7.14: Pollution Rates per kg-Recyclable Material Cleaned

Greenhouse Gases [g-pollutant/kg-PCC]			Criteria Pollutants [g-pollutant/kg-PCC]				Additional Pollutants [g-pollutant/kg-PCC]				
CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
104	0.27	0.0002	0.81	0.13	0.000	0.06	0.25	0.000002	0.02	0.09	N/R

The BEES database also provides some use-phase estimates regarding processing time and electricity requirements. It is estimated, based on area cleaned and a variety of vacuum sizes, that it would take approximately 12.5min to clean 92.9m^2 of carpeting. This translates to an estimated time of 0.05min/kg-carpet cleaned (a throughput rate of 1200kg-recycable material/hr) with an electricity requirement of 0.15kWh/kg-recyclable material (NIST, 2007). The estimated throughput rate will help to determine the social impact or labor potential associated with cleaning and re-purposing PCC. An hourly wage rate of $10.14 with a relative standard error of 2.1% for the Janitors and Cleaners, Except Maids and Housekeeping Cleaners (SOC code: 37-2011) occupational group will be used to assess the social and economic impacts (BLS, 2007). However, in order to fully determine the economic impact of this process, not only will labor wages and electricity bills need to be calculated, but the cost of the actual cleaner is required as well. An internet search using Google through their Shopping search engine, with key words "HOST Dry Carpet Cleaner," unveils that the lowest unit price for the HOST Dry Carpet Cleaning System is approximately $2.91/kg-HOST. This translates to a functional unit cost for cleaning materials of approximately 5¢/kg-carpet cleaned. The LCI dataset for this dry chemical cleaning process is found in Table 7.13: Pollution Rates per kg-HOST and Table 7.14: Pollution Rates per kg-Recyclable Material Cleaned.

Table 7.15: Carpet Cleaning Requirements per Kilogram-Recyclable Material

kWh	# laborers	min/laborer	¢-labor	¢-material	¢-energy
0.15	1	0.05	0.08	0.05	0.08

7.12 Unit Process Summary Inventory

7.12.1 Machine Specifications

The following table includes a summary of the values based on machine specifications for the variables (defined in Section 7.1.1) used to determine the electricity consumed by each mechanical process per kg-material processed. All of these numbers below represent the baseline process specifications for further study.

Table 7.16: Machine Specification Process Summary for Mechanical Processes

Process	M_i	T_i	*LF*	*eff*	energy required
[units]	[hp]	[kg-processed/hr]			[kWh/kg-processed]
baling	108	38100	1	100%	0.002116913
shredding	269	3580	1	100%	0.056114302
grinding	200	2720	1	100%	0.054911765
centrifuge	636	2000	1	100%	0.2374824
pelletizing	460	18000	1	100%	0.019084889
reactor	500	4536	1	100%	0.082319224
carding	200	550	1	100%	0.271563636
needlepunch	200	1778	1	100%	0.084022221
depolymerization	500	4536	1	100%	0.082319224
dryer	150	4536	1	100%	0.024695767

7.12.2 Environmental Inventory

This environmental inventory summary is created from emissions resulting from energy (electricity) use specifications, which are summarized in Table 7.16, and any chemical pollution rates discussed in this chapter. All of the pollutants in the following table are represented on a g-pollutant per kg-material processed basis.

Table 7.17: Environmental Inventory Process Summary [g-pollutant/kg-processed]

Process	CO_2	CH_4	N_2O	SO_2	NO_x	Pb	CO	VOCs	Hg	HC	PM	SO_x
baling	1.33	N/R	N/R	0.009	0.002	N/R	N/R	N/R	0.00000003	N/R	N/R	N/R
shredding	35.34	N/R	N/R	0.232	0.043	N/R	N/R	N/R	0.0000007	N/R	N/R	N/R
grinding	34.58	N/R	N/R	0.227	0.042	N/R	N/R	N/R	0.0000007	N/R	N/R	N/R
centrifuge	149.55	N/R	N/R	0.981	0.183	N/R	N/R	N/R	0.000003	N/R	N/R	N/R
pelletizing	12.02	N/R	N/R	0.079	0.015	N/R	N/R	N/R	0.0000002	N/R	N/R	N/R
carding	171.01	N/R	N/R	1.122	0.209	N/R	N/R	N/R	0.000003	N/R	N/R	N/R
needlepunch	52.91	N/R	N/R	0.347	0.065	N/R	N/R	N/R	0.000001	N/R	N/R	N/R
depolymerization	1174	12	0.00	5.16	3.07	0.000001	0.91	0.00004	0.0002	0.64	0.52	N/R
dryer	15.55	N/R	N/R	0.102	0.019	N/R	N/R	N/R	0.0000003	N/R	N/R	N/R
cleaning	104	0.27	0.0002	0.810	0.130	0	0.06	0.25	0.000002	0.02	0.09	N/R

7.12.3 Economic Inventory

The economic inventory summary below captures the operational cost burdens associated with the various components of each process including labor, energy, materials, and total cost. All inventories are in a $-category per kg-material processed unit form.

Table 7.18: Economic Inventory Process Summary [$-category/kg-processed]

Process	$-labor	$-electricity	$-materials	$-TOTAL
baling	$0.0003	$0.0001	$0.0000	$0.0004
shredding	$0.0074	$0.0031	$0.0000	$0.0105
grinding	$0.0097	$0.0031	$0.0000	$0.0128
centrifuge	$0.0075	$0.0133	$0.0000	$0.0208
pelletizing	$0.0008	$0.0011	$0.0000	$0.0018
carding	$0.0238	$0.0152	$0.0000	$0.0390
needle punch	$0.0074	$0.0047	$0.0000	$0.0121
depolymerization	$0.0044	$0.0046	$0.4111	$0.4201
dryer	$0.0044	$0.0014	$0.0000	$0.0057
cleaning	$0.0085	$0.0084	$0.0050	$0.0218

7.12.4 Social Inventory

The social inventory summary outlined in Table 7.19 captures all of the implications concerning labor and wage potentials for each process in the appropriate functional unit, typically per kg-material processed.

Table 7.19: Social Inventory Process Summary

Process	time [hr per kg-processed]	time [min per kg-processed]	time [sec per kg-processed]	# laborers per process	wage rates [$-labor per kg-processed]
baling	0.00003	0.0016	0.094	1	$0.0003
shredding	0.0003	0.0168	1.006	2	$0.0074
grinding	0.0004	0.0221	1.324	2	$0.0097
centrifuge	0.0005	0.0300	1.8	1	$0.0075
pelletizing	0.0001	0.0033	0.2	1	$0.0008
carding	0.0018	0.1091	6.545	1	$0.0238
needle punch	0.0006	0.0338	2.025	1	$0.0074
depolymerization	0.0002	0.0132	0.794	1	$0.0044
dryer	0.0002	0.0132	0.794	1	$0.0044
dry cleaning	0.0008	0.05	3	1	$0.0085

CHAPTER 8

INDIVIDUAL END-OF-LIFE SCNEARIO IMPACT ASSESSMENT

8.1 Waste Disposal - Landfill

The landfill scenarios in this section comprise the baseline case for the PCC EOL comparative studies. They represent, for the most part, the current practices of PCC disposal or the destiny of the majority of the carpet disposed of annually in the U.S. Because this study assumes a corporate or original manufacturer responsibility approach to this study, the acquisition of virgin materials needed to replace the potentially recyclable material that is discarded is also included in the landfill scenarios. This affects the economic and environmental impacts of each EOL scenario, but adds nothing to the social impact categories discussed. Additionally, all of the impacts discussed in the following sections represent the annual impacts based on the average PIEs. Due to the linearity of the LCA, all of the collection process impacts and virgin material impacts described in this section have annual ranges of ±17% resulting from the PIEs bounds discussed in Chapter 5.

Additionally, the collection scheme assessed here, unless otherwise noted, is the County Seat to nearest landfill scenario as described in Sections 5.2.1 for PCC-tile and 5.2.2.1 for PCC-broadloom. These two collection scenarios offer a representative basis for the overall landfill EOL scenarios. The affects of collection variance on the social, economic and environmental impacts of the various other PCC EOL scenarios will be discussed in Chapter 10 during the comparative assessments. There, the collection schemes will offer insight into the parameters and improvements that would tip the LCA recommendations in one direction or another.

Before the individual PCC EOL landfill scenarios are discussed according to carpet type, the overarching landfill scenario, where all of the PCC, tile and broadloom, is collected and disposed of in the local county landfills is outlined in this section. Because this is the generic case, the acquisition of virgin materials needed to replace the dumped materials is not included in the assessment. Therefore, the only environmental and social impacts are a direct result of the PCC collection. However, there is a spread of economic impacts based on fuel, labor, and landfill tipping fees. The major money drain in this scenario appears to be the tipping fee, which accounts for 73% of the total costs of the PCC EOL landfill scenario.

Environmental Impact

The individual environmental impacts, based solely on the collection of PCC and its transportation to a local landfill is outlined in Table 8.1. This assessment is followed by an aggregated impact assessment of the generic PCC landfill scenario based on GWP, CAPs, Smog Potential, and EcoToxicity; these results are displayed in

Table 8.2.

Table 8.1: Post Consumer Carpet Landfill Scenario
- Individual Environmental Impact Categories

[grams-pollutant]	pollutant	Collection	per kg-collected PCC
Greenhouse Gases	CO_2	781,033,000	17.60
	CH_4	5,000	0.0001
	N_2O	5,000	0.0001
Criteria Air Pollutants	SO_2	99,750	0.002
	NO_x	4,848,000	0.109
	Pb	0	0.00
	CO	18,803,000	0.424
Additional Pollutants	VOCs	0	0.00
	Hg	0	0.00
	HC	1,576,000	0.036
	PM	120,000	0.003
	SO_x	0	0.00

Table 8.2: Post Consumer Carpet Landfill Scenario

Environmental Equivalencies Impact Categories

[grams-pollutant equivalent]	pollutant	Collection	per kg-collected PCC
Global Warming Potential [CO_2 Equivalents]	CO_2	781,034,000	17.60
	CH_4	115,000	0.003
	N_2O	1,476,000	0.033
	TOTAL	**782,625,000**	**17.63**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	1,400	0.00003
	NO_x	9,700	0.0002
	PM	5,500	0.0001
	TOTAL	**16,600**	**0.0004**
Smog Potential [NO_x Equivalents]	NO_x	6,011,000	0.135
	HC	1,526,000	0.034
	PM	5,500	0.0001
	TOTAL	**7,542,000**	**0.170**
EcoToxicity [g 2,4-D Equivalents]	Hg	0	0.00
	Pb	0	0.00
	CO	376,000	0.008
	TOTAL	**376,000**	**0.008**

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Social Impact

The social impact is limited to the time and wage requirements associated with the collection and transportation portion of the PCC. For this baseline scenario, there is an estimated employment potential of 18,136±17% annual hours. That translates to an annual wage payout of $301,060±17%. This correlates to 0.0004 hours per kg PCC (approximately 1.5 seconds per kg-PCC) and roughly 0.7¢ per kg PCC.

Economic Impact

The economic impact occurs as a result of 1) fuel costs, 2) labor costs, and 3) tipping fees in this generic PCC landfill EOL scenario. The break down is located in Table 8.3. It is clear that the major economic drain in this scenario, at 73% of the total costs, is the tipping fee associated with the dumping of the PCC in the local landfills. Thus, in actuality, it would cost approximately 5.1¢ to dispose 1kg PCC.

Table 8.3: Post Consumer Carpet Landfill Scenario - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg collected PCC	% Total Impact
Fuel	\$311, 796	0.7¢	14%
Labor	\$301, 060	0.7¢	13%
Tipping	\$1, 628, 779	3.7¢	73%
TOTAL	**\$2, 241, 635**	**5.1¢**	

8.1.1 Broadloom Carpet and Repurposed Source Reduction

This particular EOL landfill scenario includes the collection and disposal of all PCC-broadloom and the replacement of the potentially repurpose-able nylon PCC-broadloom with new nylon broadloom carpet representative of the current virgin broadloom carpets on the market today. From the impact results posted in Table 8.4 through Table 8.6, it is clear that nearly 100% of the environmental and economic impacts discussed are a result of the acquisition of new broadloom carpet. Again, because this is a waste disposal scenario, the only labor potential generated is a direct result of the collection and transportation of the PCC-broadloom to local landfills.

Environmental Impact

Based on the aggregated environmental impacts displayed in Table 8.5, it is clear that nearly 100% of the environmental burdens are associated with the manufacturing and acquisition of the virgin nylon broadloom carpet. This scenario is slightly misleading, in that we have assumed that 100% of the nylon PCC-broadloom is repurpose-able; this drives the total annual impacts upwards. However, even on a per kg-repurpose-able PCC-broadloom basis, the environmental impacts associated with the virgin carpet are still astronomically higher than the per kg impacts of collection.

Table 8.4: Broadloom Carpet and Repurposed Source Reduction Landfill Scenario

- Individual Environmental Impact Categories

[grams-pollutant]	pollutant	Collection	Virgin Material	TOTAL	per kg repurpose-able PCC-broadloom
Greenhouse Gases	CO_2	702,921,000	169,881,000,000	170,584,000,000	5,340
	CH_4	4,500	629,545,000	629,549,000	19.70
	N_2O	4,500	13,102,000	13,107,000	0.41
Criteria Air Pollutants	SO_2	89,800	829,273,000	829,363,000	25.95
	NO_x	4,363,000	629,225,000	633,588,000	19.83
	Pb	0	0	0	0.00
	CO	16,922,000	182,153,000	199,075,000	6.23
Additional Pollutants	VOCs	0	0	0	0.00
	Hg	0	1,600	1,600	0.00
	HC	1,418,000	98,426,000	99,845,000	3.12
	PM	107,700	179,916,000	180,023,000	5.63
	SO_x	0	0	0	0.00

Table 8.5: Broadloom Carpet and Repurposed Source Reduction Landfill Scenario - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Virgin Material
Global Warming Potential [CO_2 Equivalents]	CO_2	0.41%	99.59%
	CH_4	0.00%	100.00%
	N_2O	0.03%	99.97%
	TOTAL	**0.37%**	**99.63%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	0.01%	99.99%
	NO_x	0.69%	99.31%
	PM	0.06%	99.94%
	TOTAL	**0.07%**	**99.93%**
Smog Potential [NO_x Equivalents]	NO_x	0.69%	99.31%
	HC	1.42%	98.58%
	PM	0.06%	99.94%
	TOTAL	**0.76%**	**99.24%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	100.00%
	Pb	0.00%	0.00%
	CO	8.50%	91.50%
	TOTAL	**0.17%**	**99.83%**

Social Impact

The social impact is limited to the time and wage requirements associated with the collection and transportation portion of the PCC-broadloom. Although the virgin materials are within the same industry and thus arguably would utilize the same employees, the labor required for the manufacturing and acquisition of the virgin carpets are not considered because the jobs created are not new. This study considers the labor potential only, and thus only includes the hours and wages associated with the creation of new jobs resulting from the EOL scenario being assessed. Thus, for this average scenario, there is an estimated employment potential of only 16,322±17% annual hours due to the labor required to collect and transport the PCC-broadloom to a local landfill. This translates to an annual wage payout of $270,951±17%, which correlates to 0.0005 hours per kg PCC-broadloom (approximately 1.8 seconds per kg repurpose-able PCC-broadloom) and roughly 0.8¢ per kg repurpose-able PCC-broadloom.

Economic Impact

The economic impact occurs as a result of 1) fuel costs, 2) labor costs, 3) tipping fees and 4) virgin material costs, which for this scenario is new broadloom carpet representative of the current market and replaced in an amount equal to that disposed. Again, the economic impact is dominated by the cost of the virgin materials. Additionally, less than 1% of the total cost is attributable to labor.

Table 8.6: Broadloom Carpet and Repurposed Source Reduction Landfill Scenario - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg repurpose-able PCC-broadloom	% Total Impact
Fuel	$280,612	0.9¢	0.24%
Labor	$270,951	0.8¢	0.23%
Tipping	$1,440,664	4.5¢	1.23%
Virgin Materials	$115,363,277	$3.61	98.30%
TOTAL	$117,355,504	$3.67	

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8.1.2 Carpet Tile and Recyclable Polyvinylchloride

In this scenario, only the PCC-tile is collected and transported to local landfills. However, the entire carpet is not replaced, only the percentage, by weight, of the PVC backing material disposed is acquired in virgin materials and added into the impact assessment, which effects both the economic and environmental impacts, of this EOL scenario. And of that backing material, only a portion of the potentially recapture-able material has a market value. Again, the only labor potential generated is a result of the transportation of PCC-tile. The environmental and economic impacts are again predominately influenced by the acquisition of the virgin materials, in this case the PVC. Although, the percentage of impacts attributed to the virgin materials is not as high in this scenario as in others, this is primarily a result of the low recovery potential of recyclable PVC from each kilogram of PCC-tile collected.

Environmental Impact

The aggregated environmental impacts are dominated by the virgin PVC; its impact ranges from about 95% of the Smog Potential to a just under 100% in the Human Health: CAPs and EcoToxicity categories. On a per kg-reclaimable PVC basis, this EOL scenario would emit nearly 780-CO_2 and other pollutants in the 0-10g range per kg-PVC.

Table 8.7: Carpet Tile and Recyclable Polyvinylchloride Landfill Scenario - Individual Environmental Impact Categories

[grams-pollutant]	pollutant	Collection	Virgin Material	TOTAL	per kg PVC backing
Greenhouse Gases	CO_2	78,270,000	2,683,000,000	2,761,300,000	780
	CH_4	500	10,270,000	10,270,000	2.89
	N_2O	500	27,000	27,000	0.01
Criteria Air Pollutants	SO_2	1,000	16,140,000	16,140,000	4.55
	NO_x	486,000	11,220,000	11,710,000	3.30
	Pb	0	120	120	0.00003
	CO	1,880,000	5,370,000	7,250,000	2.04
Additional	VOCs	0	506,000	510,000	0.14

Pollutants	**Hg**	0	40	40	0.00001
	HC	158,000	1,860,000	2,020,000	0.57
	PM	12,000	2,660,000	2,680,000	0.75
	SO_x	78,270,000	10,430,000	88,690,000	24.98

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Table 8.8: Carpet Tile and Recyclable Polyvinylchloride Landfill Scenario - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Virgin Material
Global Warming Potential [CO_2 Equivalents]	CO_2	2.83%	97.17%
	CH_4	0.00%	100.00%
	N_2O	1.84%	98.16%
	TOTAL	**2.61%**	**97.39%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	0.01%	99.99%
	NO_x	4.15%	95.85%
	PM	0.45%	99.55%
	TOTAL	**0.41%**	**99.59%**
Smog Potential [NO_x Equivalents]	NO_x	4.15%	95.85%
	HC	7.81%	92.19%
	PM	0.45%	99.55%
	TOTAL	**4.55%**	**95.45%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	100.00%
	Pb	0.00%	0.00%
	CO	25.99%	74.01%
	TOTAL	**0.77%**	**99.23%**

Social Impact

The social impact is limited to the time and wage requirements associated with the collection and transportation portion of the PCC-tile. For this average scenario, there is an estimated employment potential of 1,817±17% annual hours. That translates to an annual wage payout of $30,169±17%. This correlates to 0.0001 hours per kg-PVC (approximately 0.4 seconds per kg PVC backing) and roughly 0.9¢ per kg-PVC backing.

Economic Impact

The economic impact occurs as a result of 1) fuel costs, 2) labor costs, 3) tipping fees and 4) virgin material costs, which for this scenario is virgin PVC to be used in carpet tile backing replacing in an amount equal to the PVC disposed. The economic impact of the virgin material is around 90%. Additionally, nearly 97% of the total costs are attributable to potentially avoidable expenses, tipping fees and virgin materials, if the PCC-tile EOL strategy was managed differently.

Table 8.9: Carpet Tile and Recyclable Polyvinylchloride Landfill Scenario - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg PVC-backing	% Total Impact
Fuel	\$31,244	0.88¢	1.33%
Labor	\$30,169	0.85¢	1.29%
Tipping	\$162,878	4.59¢	6.96%
Virgin Materials	\$2,117,124	59.63¢	90.42%
TOTAL	**\$2,341,415**	65.94¢	

8.1.3 Broadloom Carpet and Recyclable Nylon 6

The landfill EOL scenario includes the collection of all PCC-broadloom carpet and the replacement of N6 face fibers, by weight, with virgin N6 pellets. This inclusion is modeled to establish similar boundaries with the PMR-N6 EOL scenario and affects both the economic and environmental impact categories. Based on the impact assessments displayed in Table 8.10 through Table 8.12 it is clear that over 90% of the negative impacts in both the environmental and economic categories is a direct result of the acquisition of virgin N6 pellets.

Environmental Impact

Essentially 100% of the negative environmental impacts of this EOL landfill scenario are attributable to the manufacturing and acquisition of the virgin N6 pellets, although the collection impacts are definitely not negligible.

Table 8.10: Broadloom Carpet and Recyclable Nylon 6 Landfill Scenario - Individual Environmental Impact Categories

[grams-pollutant]	pollutant	Collection	Virgin Material	TOTAL	per kg N6
Greenhouse Gases	CO_2	702,921,000	25,512,000,000	26,215,000,000	3,570
	CH_4	4,500	344,495,000	344,500,000	46.87
	N_2O	4,500	63,284,000	63,288,000	8.61
Criteria Air Pollutants	SO_2	89,800	101,063,000	101,152,000	13.76
	NO_x	4,363,000	97,388,000	101,751,000	13.84
	Pb	0	22	22	0.00
	CO	16,922,000	59,021,000	75,943,000	10.33
Additional Pollutants	VOCs	0	147,000	147,000	0.02
	Hg	0	300	300	0.00004
	HC	1,418,000	29,474,000	30,892,000	4.20
	PM	108,000	10,952,000	11,059,000	1.50
	SO_x	0	294,00	294,000	0.04

Table 8.11: Broadloom Carpet and Recyclable Nylon 6 Landfill Scenario - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Virgin Material
Global Warming Potential [CO_2 Equivalents]	CO_2	2.68%	97.32%
	CH_4	0.00%	100.00%
	N_2O	0.01%	99.99%
	TOTAL	**1.33%**	**98.67%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	0.09%	99.91%
	NO_x	4.29%	95.71%
	PM	0.97%	99.03%
	TOTAL	**0.70%**	**99.30%**
Smog Potential [NO_x Equivalents]	NO_x	4.29%	95.71%
	HC	4.59%	95.41%
	PM	0.97%	99.03%
	TOTAL	**4.34%**	**95.66%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	100.00%
	Pb	0.00%	0.00%
	CO	22.28%	77.72%
	TOTAL	**0.93%**	**99.07%**

Social Impact

The social impact is limited to the time and wage requirements associated with the collection and transportation portion of the PCC-broadloom. For this average scenario, there is an estimated employment potential of 16,322±17% annual hours. That translates to an annual wage payout of \$270,951±17%. This correlates to 0.002 hours per kg-N6 (approximately 7 seconds per kg-N6) and roughly 4¢ per kg-N6.

Economic Impact

The economic impact is as a result of 1) fuel costs, 2) labor costs, 3) tipping fees and 4) virgin material costs, which for this scenario is the N6 monomer, caprolactam. For this scenario, as with most of the EOL landfill scenarios, approximately 90% of the costs incurred could be reduced in the PCC-broadloom EOL scenario was managed differently.

Table 8.12: Broadloom Carpet and Recyclable Nylon 6 Landfill Scenario - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg-N6	% Total Impact
Fuel	\$280,612	3.0¢	1.45%
Labor	\$270,951	2.9¢	1.40%
Tipping	\$1,465,901	20¢	7.60%
Virgin Materials	\$17,272,535	\$2.35	89.54%
TOTAL	\$19,289,999	\$2.62	

8.1.4 Broadloom Carpet without Recyclable Material Replacement

This scenario is used to establish a baseline comparison for the collection and disposal of all PCC-broadloom carpet. There is no material replacement, thus all of the impacts are a direct result of the collection and transportation of the PCC-broadloom to local landfills. Thus, all of the social impact potential is a result of the transportation times. However, of the overall economic impact about 73% is attributable to tipping fees alone.

Environmental Impact

Based on collection costs alone, this scenario leads to pollution rates of approximately 18g-CO_2 equivalents, 0.004 microDALYs, 0.17g-NOx equivalents, and 0.008 g 2,4-D Equivalents per kg PCC-broadloom.

Table 8.13: Broadloom Carpet without Recyclable Material Replacement Landfill Scenario - Individual Environmental Impact Categories

[grams-pollutant]	pollutant	Collection	Annual Impact per kg PCC-broadloom
Greenhouse Gases	**CO_2**	702,921,000	17.60
	CH_4	4,500	0.0001
	N_2O	4,500	0.0001
Criteria Air Pollutants	**SO_2**	89,800	0.002
	NO_x	4,363,000	0.109
	Pb	0.00	0.00
	CO	16,922,000	0.42
Additional Pollutants	**VOCs**	0.00	0.00
	Hg	0.00	0.00
	HC	1,418,000	0.04
	PM	107,700	0.003
	SO_x	0.00	0.00

Table 8.14: Broadloom Carpet without Recyclable Material Replacement Landfill Scenario - Environmental Equivalencies Impact Categories

	pollutant	Collection	Annual Impact per kg PCC-broadloom
Global Warming Potential [g CO_2 Equivalents]	CO_2	702,921,000	17.60
	CH_4	103,200	0.003
	N_2O	1,329,000	0.03
	TOTAL	**704,353,000**	**17.63**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	1,300	0.00003
	NO_x	8,700	0.0002
	PM	5,000	0.0001
	TOTAL	**15,000**	**0.0004**
Smog Potential [g NO_x Equivalents]	NO_x	5,410,000	0.14
	HC	1,373,000	0.03
	PM	5000	0.0001
	TOTAL	**6,788,000**	**0.17**
EcoToxicity [g 2,4-D Equivalents]	Hg	0	0.00
	Pb	0	0.00
	CO	338,000	0.008
	TOTAL	**338,000**	**0.008**

Social Impact

The social impact is limited to the time and wage requirements associated with the collection and transportation portion of the PCC-broadloom. For this average scenario, there is an estimated employment potential of 16,322±17% annual hours. That translates to an annual wage payout of $270,951±17%.

Economic Impact

The economic impact is as a result of 1) fuel costs, 2) labor costs, and 3) tipping fees only. There is no replacement of potential recyclable material and thus no costs associated with the acquisition of virgin materials. The majority of the costs incurred are attributable to the tipping fees associated with the disposal of the PCC-broadloom. This could potentially be reduced if the EOL scenario were managed differently.

Table 8.15: Broadloom Carpet without Recyclable Material Replacement Landfill Scenario - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg PCC-broadloom	% Total Impact
Fuel	$280,612	0.7¢	13.91%
Labor	$270,951	0.7¢	13.43%
Tipping	$1,465,901	3.7¢	72.66%
TOTAL	**$2,017,464**	**5.1¢**	

8.1.5 Broadloom Carpet with Recyclable Nylon Fibers Replaced with Carpet Underlay

This scenario assesses the impacts associated with the collection and transportation of all Nylon PCC-broadloom carpet and the replacement of the Nylon broadloom carpet, by weight, with carpet underlay representative of the current market trends in costs, recycled content, and environmental impacts. The results demonstrate that over 90% of the negative environmental impacts of this particular scenario are a direct consequence of the newly manufactured carpet underlay; the underlay also contributes to approximately 88% of the total EOL costs incurred. However, like all of the other waste disposal scenarios, the entire social impact potential is a direct result of the time and labor required in the collection and transportation of the PCC-broadloom.

Environmental Impact

Approximately 90-99% of the aggregated environmental impacts are attributable to manufacturing and acquisition of the virgin carpet underlay.

Table 8.16: Broadloom with Recyclable Nylon Material Replacement by Underlay Landfill Scenario - Individual Environmental Impact Categories

[grams-pollutant]	pollutant	Collection	Carpet Underlay	Annual Impact per kg PCC-Nylon Fibers
Greenhouse Gases	CO_2	702,921,000	12,701,000,000	912
	CH_4	4,500	50,186,000	3.410
	N_2O	4,500	353,000	0.020
Criteria Air Pollutants	SO_2	89,800	93,492,000	6.37
	NO_x	4,363,000	37,485,000	2.85
	Pb	0	0	0.00
	CO	16,922,000	28,665,000	3.10
Additional Pollutants	VOCs	0	0	0.00
	Hg	0	147	0.00001
	HC	1,418,000	14,259,000	1.07
	PM	108,000	11,319,000	0.78
	SO_x	0	0	0.00

Table 8.17: Broadloom with Recyclable Nylon Material Replacement by Underlay Landfill Scenario - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Carpet Underlay
Global Warming Potential [CO_2 Equivalents]	CO_2	5.24%	94.76%
	CH_4	0.01%	99.99%
	N_2O	1.26%	98.74%
	TOTAL	**4.80%**	**95.20%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	0.10%	99.90%
	NO_x	10.43%	89.57%
	PM	0.94%	99.06%
	TOTAL	**0.78%**	**99.22%**
Smog Potential [NO_x Equivalents]	NO_x	10.43%	89.57%
	HC	9.05%	90.95%
	PM	0.94%	99.06%
	TOTAL	**10.04%**	**89.96%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	100.00%
	Pb	0.00%	100.00%
	CO	37.12%	62.88%
	TOTAL	**1.84%**	**98.16%**

Social Impact

The social impact is limited to the time and wage requirements associated with the collection and transportation portion of the PCC-broadloom. For this average scenario, there is an estimated employment potential of 16,322±17% annual hours or 4sec/kg recyclable PCC-Nylon Fibers. This translates to an annual wage payout of $270,951±17% or 1.84¢/kg recyclable PCC-Nylon Fibers.

Economic Impact

The economic impact is as a result of 1) fuel costs, 2) labor costs, 3) tipping fees only and 4) the cost of new carpet underlay. The virgin materials, in this case, account for approximately 88% of the total costs incurred. Additionally, less than 2% of the total cost is labor related; thus 98% of the costs could potentially be reduced if the EOL scenario were managed differently.

Table 8.18: Broadloom with Recyclable Nylon Material Replacement by Underlay Landfill Scenario - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg PCC-Nylon Fibers	% Total Impact
Fuel	$280,612	1.91¢	1.77%
Labor	$270,951	1.84¢	1.71%
Virgin Materials	$13,965,028	95.00¢	88.19%
Tipping	$1,319,311	8.08¢	8.33%
TOTAL	**$15,835,902**	**$1.08**	

8.1.6 Broadloom Carpet with Recyclable Nylon 6,6 Fibers Replaced with Glass Reinforced Nylon 6,6 Plastic Pellets

This scenario assesses the impacts associated with the collection and transportation of all PCC-broadloom carpet and the replacement of the N66 fibers, which could potentially be recycled into glass reinforced plastic pellets, with virgin manufactured glass reinforced plastic pellets. The results indicate that over 98% of the negative environmental impacts of this particular scenario are a direct consequence of the virgin plastic pellet manufacturing. The economic costs associated with the acquisition of the virgin pellets are not included in this individual landfill EOL scenario assessment because the comparative assessment will occur in the context of a SMR scenario. Thus, the products produced in the SMR scenario would exit the industry boundary and will be represented in the model by a potential monetary gain (or negative monetary value). However, it is important to consider the more generalized environmental impacts associated with the individual EOL scenarios in order to juxtapose the manufacturing of products from virgin materials against recycled-content materials in the comparative assessment; thus, the inclusion of the virgin N66 plastic pellets in the environmental impact categories here is necessary. Like all of the other waste disposal scenarios, the entire social impact potential is a direct result of the time and labor required in the collection and transportation of the PCC-broadloom.

Environmental Impact

Nearly 100% of the aggregated environmental impacts are attributable to the acquisition of the virgin glass reinforced plastic N66 pellets.

Table 8.19: Broadloom with Recyclable Nylon Material Replacement by Underlay Landfill Scenario - Individual Environmental Impact Categories

[grams-pollutant]	pollutant	Collection	Glass Reinforced N66 Pellets	Annual Impact per kg N66
Greenhouse Gases	CO_2	702,921,000	98,611,000,000	9,000
	CH_4	4,500	442,103,000	40.10
	N_2O	4,500	107,573,000	9.76
Criteria Air Pollutants	SO_2	89,800	357,841,000	32.47
	NO_x	4,363,000	315,158,000	28.98
	Pb	0	47	0.00
	CO	16,922,000	65,520,000	7.48
Additional Pollutants	VOCs	0	1,733,000	0.16
	Hg	0	158	0.00001
	HC	1,418,000	45,990,000	4.30
	PM	108,000	53,550,000	4.87
	SO_x	0	0	0

Table 8.20: Broadloom with Recyclable Nylon Material Replacement by Underlay Landfill Scenario - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Glass Reinforced N66 Pellets
Global Warming Potential [CO_2 Equivalents]	CO_2	0.71%	99.29%
	CH_4	0.00%	100.00%
	N_2O	0.00%	100.00%
	TOTAL	**0.50%**	**99.50%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	0.03%	99.97%
	NO_x	1.37%	98.63%
	PM	0.20%	99.80%
	TOTAL	**0.18%**	**99.82%**
Smog Potential [NO_x Equivalents]	NO_x	1.37%	98.63%
	HC	2.99%	97.01%
	PM	0.20%	99.80%
	TOTAL	**1.53%**	**98.47%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	100.00%
	Pb	0.00%	0.00%
	CO	20.53%	79.47%
	TOTAL	**1.66%**	**98.34%**

Social Impact

The social impact is limited to the time and wage requirements associated with the collection and transportation portion of the PCC-broadloom to the local landfills for disposal. For this average scenario, there is an estimated employment potential of 16,322±17% annual hours or about 5 sec per kg recyclable N66. This translates to an annual wage payout of $270,951±17% or 2.46¢ per kg recyclable N66.

Economic Impact

The economic impact is as a result of 1) fuel costs, 2) labor costs and 3) tipping fees. The tipping fees, in this case, account for approximately 73% of the total costs incurred. Only about 13% of the total cost is labor related. Therefore about 87% of the costs could potentially be reduced if the EOL scenario were managed differently in both distance traveled for collection and the amount of material being dumped in the landfills.

Table 8.21: Broadloom with Recyclable Nylon Material Replacement by Underlay Landfill Scenario - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg N66	% Total Impact
Fuel	$280,612	2.55¢	13.93%
Labor	$270,951	2.46¢	13.43%
Tipping	$1,465,901	13.30¢	72.66%
TOTAL	$2,017,464	18.31¢	

8.2 Material Reclamation

The Material Reclamation scenarios discussed in this section include repurposing of PCC-broadloom, closed-loop recycling of PVC from PCC-tiles and N6 from PCC-broadloom, and open-loop recycling of Nylon broadloom into carpet underlay and N66 face fibers into glass reinforced plastic pellets. These scenarios are described in greater detail in Chapter 3.

Each scenario is first explored in terms of its annual impacts according to the average PIEs and the average higher-end collection scheme (refer to Chapter 6 Section 2 for more details on collection related assumptions and assessments). The effects of the PIE spread and the differences in annual miles traversed for collection are discussed in terms of deviation from the initial average impact assessments initially presented. The collection variances are individually discussed, while the variation due to PIEs is around ±17% unless otherwise noted.

8.2.1 Repurpose Material Reclamation

In this scenario, all of the PCC-broadloom is collected and the Nylon broadloom, which includes both N6 and N66 face fibers, is sorted for dry process cleaning so that it can be donated and reinstalled as flooring for its second life. Since only the Nylon carpet is repurposed, the remaining 20% of the PCC-broadloom collected is transported in

HDDV-3s at 75%TL to the nearest landfill approximately 5 miles away where a 3¢/kg tipping fee is incurred. The impacts are individually discussed below.

Environmental Impact

There appears to be a pretty even split between transportation and cleaning related pollution rates. It makes sense that the transportation portions of this EOL scenario are the major contributors to both GWP and Smog Potential where the pollution is generally more atmospheric. On the other hand, the cleaning procedure has a greater impact on CAPs and EcoToxicity where the chemicals present in the cleaning agents tend to have higher concentrations of heavier pollutants.

Table 8.22: Post Consumer Nylon Broadloom Carpet Repurpose Material Reclamation - Individual Environmental Impact Categories

[grams-pollutant]	pollutant	Upper Collection Bounds	Landfill: transportation & disposal	Dry Cleaning Process
Greenhouse Gases	CO_2	3,824,452,000	23,001,000	3,323,485,000
	CH_4	24,400	150	8,628,000
	N_2O	24,400	150	6,400
Criteria Air Pollutants	SO_2	488,400	2,900	25,885,000
	NO_x	23,738,000	143,800	4,154,000
	Pb	0	0	0
	CO	92,070,000	553,700	1,917,000
Additional Pollutants	VOCs	0	0	7,989,000
	Hg	0	0	63.91317312
	HC	7,717,000	46,400	639,000
	PM	586,000	3,500	2,876,000
	SO_x	0	0	0

Table 8.23: Post Consumer Nylon Broadloom Carpet Repurpose Material Reclamation - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Landfill: transportation & disposal	Dry Cleaning Process
Global Warming Potential [CO_2 Equivalents]	CO_2	53.33%	0.32%	46.35%
	CH_4	0.28%	0.00%	99.72%
	N_2O	78.88%	0.47%	20.64%
	TOTAL	**51.93%**	**0.31%**	**47.75%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	1.85%	0.01%	98.14%
	NO_x	84.67%	0.51%	14.82%
	PM	16.91%	0.10%	82.99%
	TOTAL	**13.90%**	**0.08%**	**86.02%**
Smog Potential [NO_x Equivalents]	NO_x	84.67%	0.51%	14.82%
	HC	91.84%	0.55%	7.61%
	PM	16.91%	0.10%	82.99%
	TOTAL	**85.78%**	**0.52%**	**13.71%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	0.00%	100.00%
	Pb	N/A	N/A	N/A
	CO	97.39%	0.59%	2.03%
	TOTAL	**19.42%**	**0.12%**	**80.46%**

Social Impact

The total annual labor potential of this EOL scenario amounts to nearly 116,000 hours. This roughly translates to 279 8-hr shifts per week or about 40 8-hr shifts per day. About 85% of this employment potential is attributable to transportation related activities. Based on the cleaning process alone, the 26,621 annual hours of labor corresponds to the potential for 64 8-hr shifts per week or 9 8-hr shifts per day.

Table 8.24: Post Consumer Nylon Broadloom Carpet Repurpose Material Reclamation - Social Impact Categories

Process	Labor Hours	sec per kg-Repurposed Broadloom	Labor Wages	¢ per kg-Repurposed Broadloom	% wage contribution
Collection	88,807	10.00	$1,474,188	4.61¢	**84.10%**
Transportation to Landfill	534	0.06	$8,866	0.02¢	0.51%
Cleaning	26,621	3.00	$269,925	0.84¢	15.40%
TOTAL	**115,960**	**13.06**	**$1,752,979**	**5.49¢**	

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Economic Impact

The annual costs resulting from the RMR EOL scenario amount to nearly $4 million. 45% of this is a result of energy consumption, and another 44% is attributable to wage pay, which is the single largest economic impact followed closely by fuel. In summary, it would cost the carpet manufacturers approximately 12.38¢ per kilogram repurpose PCC-broadloom. This is huge savings when compared against the current market price of broadloom carpet which is averaging around $3.61 per kg-broadloom.

Table 8.25: Post Consumer Nylon Broadloom Carpet Repurpose Material Reclamation - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg PCC-repurposed	% Total Impact
Fuel	$1,535,938	4.8¢	38.82%
Electricity	$267,956	0.8¢	6.77%
ENERGY TOTAL	**$1,803,894**	**5.6¢**	**45.60%**
Labor	**$1,752,979**	**5.5¢**	**44.31%**
Material – Cleaning Products	$159,783	0.5¢	4.04%
Tipping	$239,674	0.8¢	6.06%
TOTAL MATERIAL	**$399,457**	**1.2¢**	10.10%
TOTAL	**$3,956,330**	12.38¢	

Change Due to Collection Strategy

If the geographically dispersed collection scheme, outlined in Section 6.2.2.3, were employed instead of the generic estimates used for the base assessment, changes in the various impacts would occur in the rages outlined in Table 8.26. This collection scheme results in decreased impacts, which is undeniably beneficial in all categories except labor wages. However, there is a potential 71% total cost savings and environmental impact reduction around 50%.

Table 8.26: Percent of Impact Change due to Collection Scheme

Impact Category	% change
Distance	-75%
Labor Wages	-75%
Collection Costs	-71%
Total Cost	-71%
Global Warming Potential	-55%
Human Health: Criteria Air Pollutants	-52%
Smog Potential	-46%
EcoToxicity	-46%

8.2.2 Primary Material Reclamation

The scenarios discussed in this section refer to the closed-loop recycling EOL activities for both PVC, present in PCC-tile, and N6 face fibers from PCC-broadloom. In the scenarios either all of the PCC-tile or all of the PCC-broadloom is collected, yet only the portion that includes the recyclable materials is processed to separate the recyclable materials.

8.2.2.1 Polyvinylchloride

In this scenario, all of the PCC-tile is collected and delivered to LaGrange where the PCC-tile is size reduced and separated in order to recapture the PVC backing materials. The backing materials captured include the PVC, softeners, and $CaCO_3$ filler; however, only the soft PVC portion has any real market value. The trash is transported to the local landfill while the reclaimed PVC backing materials are pelletized for reuse in new carpet backing. For a full description and diagram of the PVC EOL recycling scenario, refer to Section 3.4.

Environmental Impact

The separation process is the most energy consuming process of all the EOL activities in this scenario; consequently it is the major contributor in three out of four of the aggregated environmental impact categories. The exception is Smog Potential in which the collection process is attributable for approximately 63% of the impact. The transportation of waste to the local landfill contributes the least to the overall environmental impacts; this is closely followed by the baling process.

Table 8.27: Post Consumer Carpet Tiles for Polyvinylchloride Primary Material Reclamation - Individual Environmental Impact Categories

[g-pollutant]	pollutant	Collection	Bale	Shred	Grind	Separate	Pelletize	Landfill: transportation & disposal
Greenhouse Gasses	CO_2	400181387	5916873	156842129	153480982	663774550	663774550	2556495
	CH_4	2555	0	0	0	0	0	16.325
	N_2O	2555	0	0	0	0	0	16.325
Criteria Air Pollutants	SO_2	5111	38804	1028612	1006569	4353207	4353207	32.65
	NO_x	2483884	7235	191775	187665	811615	811615	15868
	Pb	0	0	0	0	0	0	0
	CO	9633996	0	0	0	0	0	61545
Additional Pollutants	VOCs	0	0	0	0	0	0	0
	Hg	0	0.113	2.99	2.92	12.65	12.65	0
	HC	807518	0	0	0	0	0	5159
	PM	61330	0	0	0	0	0	392
	SO_x	0	0	0	0	0	0	0

Table 8.28: Post Consumer Carpet Tiles for Polyvinylchloride Primary Material Reclamation - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Bale	Shred	Grind	Separate	Pelletize	Landfill: transportation & disposal
Global Warming Potential [CO_2 Equivalents]	CO_2	28.07%	0.42%	11.00%	10.77%	46.57%	2.99%	0.18%
	CH_4	99.37%	0.00%	0.00%	0.00%	0.00%	0.00%	0.63%
	N_2O	99.37%	0.00%	0.00%	0.00%	0.00%	0.00%	0.63%
	TOTAL	**28.12%**	**0.41%**	**11.00%**	**10.76%**	**46.54%**	**2.99%**	**0.18%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	0.08%	0.58%	15.32%	15.00%	64.86%	4.17%	0.00%
	NO_x	57.14%	0.17%	4.41%	4.32%	18.67%	14.94%	0.37%
	PM	99.37%	0.00%	0.00%	0.00%	0.00%	0.00%	0.63%
	TOTAL	**7.92%**	**0.53%**	**13.92%**	**13.62%**	**58.92%**	**5.04%**	**0.05%**
Smog Potential [NO_x Equivalents]	NO_x	57.14%	0.17%	4.41%	4.32%	18.67%	14.94%	0.37%
	HC	99.37%	0.00%	0.00%	0.00%	0.00%	0.00%	0.63%
	PM	99.37%	0.00%	0.00%	0.00%	0.00%	0.00%	0.63%
	TOTAL	**62.53%**	**0.15%**	**3.85%**	**3.77%**	**16.28%**	**13.03%**	**0.40%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	0.58%	15.34%	15.01%	64.90%	4.17%	0.00%
	Pb	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	CO	99.37%	0.00%	0.00%	0.00%	0.00%	0.00%	0.63%
	TOTAL	**28.07%**	**0.42%**	**11.00%**	**10.77%**	**46.57%**	**2.99%**	**0.18%**

Social Impact

The total annual labor potential of this EOL scenario amounts to nearly 18,000 hours. This roughly translates to 43 8-hr shifts per week or about 6 8-hr shifts per day. About 58% of this employment potential is attributable to transportation related activities. Based on the actual recycling processes alone, the approximately 8,300 annual hour of labor corresponds to the potential for 20 8-hr shifts per week or 3 8-hr shifts per day. And, the largest employment wage potential based solely on the recycling process procedures is the grinding process. This is closely followed by the separation and shredding phases.

Table 8.29: Post Consumer Carpet Tiles for Polyvinylchloride Primary Material Reclamation - Social Impact Categories

Process	Labor Hours	time per kg-reclaimed PVC	Labor Wages	cost per kg-reclaimed PVC backing	% wage contribution
Collection	9,292	9.4sec	$154,255	4.34¢	58.05%
Bale	116	0.12sec	$1,375	0.04¢	0.52$
Shred	2,480	2.5sec	$32,755	0.92¢	12.33%
Grind	3,264	3.3sec	$43,111	1.21¢	16.22%
Separate	2,220	2.2sec	$33,244	0.94¢	12.51%
Pelletize	197	0.2sec	$2,718	0.08¢	1.02%
Transportation to Landfill	60	0.1sec	$985	0.03¢	0.37%
TOTAL	17,430	18sec	$265,726	7.48¢	

Economic Impact

The annual costs resulting from the PMR-PVC EOL scenario amount to a little over $540,000. 46% of this is a result of energy consumption, and another 49% is attributable to wage pay, which is the single largest economic impact followed by fuel, which accounts for 29% of the total cost. In summary, it would cost the carpet manufacturers approximately 15.21¢ per kilogram backing materials to recycle the PVC when the current market price is $1.59 per kg-PVC.

Table 8.30: Post Consumer Carpet Tiles for Polyvinylchloride Primary Material Reclamation - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg-reclaimed PVC backing	% contribution
Fuel	\$160,777	4.53¢	29.77%
Electricity	\$86,933	2.45¢	16.11%
ENERGY TOTAL	\$247,769	6.98¢	**45.87%**
Labor	\$265,726	7.48¢	49.20%
Tipping	\$26,630	0.75¢	4.93%
TOTAL	**\$540,125**	**15.21¢**	

8.2.2.2 Nylon 6

In this scenario, all of the PCC-broadloom is collected and delivered to a recycling facility where the PCC-broadloom is size reduced and separated in order to recapture the N6 face fibers from the rest of the carpet materials. The non-recyclable trash is transported to the local landfill while the reclaimed N6 undergoes a chemical deploymerization in a high heat and pressured environment in the presence of a catalysts; in this case, the catalyst will be the base NaOH. For a full description and diagram of the PMR-N6 EOL recycling scenario, refer to Section 3.4.

Environmental Impact

There is quite a dispersion of environmental impact between the various phases of the PMR-N6 EOL scenario. The collection process is the main contributor to Smog Potential of this scenario while the GWP and CAPs are dominated by the separation process. The EcoToxicity is largely impacted by the actual chemical depolymerization process. This breakdown of impact is logical considering the types of materials and energy consumptions that predominates in each of these individual processes. The transportation affecting the Smog Potential is attributable to the diesel fuel, while the

EcoToxicity of the chemical depolymerization process is due in part to the energy required to heat and pressurize the environment and the requirements of the catalyst used to facilitate the reaction.

Table 8.31: Post Consumer Carpet for Nylon 6 Primary Material Reclamation - Individual Environmental Impact Categories

[g-pollutant]	pollutant	Collection	Bale	Shred	Grind	Separate	Chemical Depoly.	Monomer Separation	Monomer Drying	Landfill: transportation & disposal
GHG	CO_2	3,824,452,000	50,311,000	1,408,704,000	1,383,548,000	5,961,836,000	1,070,526,000	201,601,000	90,721,000	98,404,000
	CH_4	24,400	0	0	0	0	76,359,000	0	0	630
	N_2O	24,400	0	0	0	0	0	0	0	630
CAPs	SO_2	48,800	330,000	9,239,000	9,074,000	39,099,000	5,362,000	1,322,000	595,000	1,300
	NO_x	23,738,000	61,500	1,722,000	1,692,000	7,290,000	2,378,000	247,000	111,000	611,000
	Pb	0	0	0	0	0	1	0	0	0
	CO	92,070,00	0	0	0	0	593,000	0	0	2,369,000
Add. Pollutants	VOCs	0	0	0	0	0	24	0	0	0
	Hg	0	1	27	26	114	120	4	2	0
	HC	7,717,000	0	0	0	0	416,000	0	0	199,000
	PM	586,000	0	0	0	0	339,000	0	0	15,100
	SO_x	0	0	0	0	0	0	0	0	0

Table 8.32: Post Consumer Carpet for Nylon 6 Primary Material Reclamation - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Bale	Shred	Grind	Separate	Chemical Deploymerize	Monomer Separation	Monomer Drying	Landfill: transportation & disposal
Global Warming Potential [CO_2 Equivalents]	CO_2	27.81%	0.37%	10.24%	10.06%	43.35%	7.78%	1.47%	0.66%	0.72%
	CH_4	0.32%	0.00%	0.00%	0.00%	0.00%	99.67%	0.00%	0.00%	0.01%
	N_2O	97.49%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.51%
	TOTAL	**27.50%**	**0.36%**	**10.11%**	**9.93%**	**42.78%**	**8.94%**	**1.45%**	**0.65%**	**0.71%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	0.08%	0.52%	14.70%	14.44%	62.20%	8.53%	2.10%	0.95%	0.00%
	NO_x	63.41%	0.16%	4.60%	4.52%	19.47%	6.35%	0.66%	0.30%	1.63%
	PM	62.32%	0.00%	0.00%	0.00%	0.00%	36.08%	0.00%	0.00%	1.60%
	TOTAL	**7.53%**	**0.48%**	**13.30%**	**13.07%**	**56.30%**	**9.56%**	**1.90%**	**0.86%**	**0.19%**
Smog Potential [NO_x Equivalents]	NO_x	63.41%	0.16%	4.60%	4.52%	19.47%	6.35%	0.66%	0.30%	1.63%
	HC	92.62%	0.00%	0.00%	0.00%	0.00%	4.99%	0.00%	0.00%	2.38%
	PM	62.32%	0.00%	0.00%	0.00%	0.00%	36.08%	0.00%	0.00%	1.60%
	TOTAL	**67.73%**	**0.14%**	**3.92%**	**3.85%**	**16.58%**	**6.18%**	**0.56%**	**0.25%**	**1.74%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	0.34%	9.40%	9.23%	39.78%	41.55%	1.35%	0.61%	0.00%
	Pb	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%
	CO	96.88%	0.00%	0.00%	0.00%	0.00%	0.62%	0.00%	0.00%	2.49%
	TOTAL	**5.14%**	**0.32%**	**8.90%**	**8.74%**	**37.67%**	**39.38%**	**1.27%**	**0.57%**	**0.13%**

Social Impact

The total annual labor potential of this EOL scenario amounts to nearly 167,000 hours. This roughly translates to 400 8-hr shifts per week or about 60 8-hr shifts per day. About 58% of this employment potential is attributable to transportation related activities. Based on the actual recycling processes alone, the approximately 77,000 annual hour of labor corresponds to the potential for 190 8-hr shifts per week or 27 8-hr shifts per day. And, the largest employment wage potential based solely on the recycling process procedures is a result of the grinding process.

Table 8.33: Post Consumer Carpet for Nylon 6 Primary Material Reclamation - Social Impact Categories

Process	Labor Hours	sec per kg-recycled N6	Labor Wages	cost per kg-recycled N6	% wage contribution
Collection	88,807	55.48	$1,474,188	25.58¢	57.37%
Bale	1,332	0.83	$15,712	0.27¢	0.61%
Shred	22,636	14.14	$299,020	5.19¢	11.64%
Grind	29,294	18.30	$386,968	6.72¢	15.06%
Carpet Material Separation	19,973	12.48	$299,194	5.19¢	11.64%
Chemical Depolymerization	1,416	0.88	$30,052	0.52¢	1.17%
Chemical Separation	1,416	0.88	$30,052	0.52¢	1.17%
Drying	1,249	0.78	$26,506	0.46¢	1.03%
Transportation to Landfill	2,285	1.43	$37,931	0.66¢	1.48%
TOTAL	**166,989**	**104**	**$2,569,571**	**44.59¢**	

Economic Impact

The annual costs resulting from the PMR-N6 EOL scenario amount to nearly $8.4 million. 28% of this is a result of energy consumption, 29% is attributable to the acquisition of the chemical materials necessary for the reaction, and approximately another 30% is attributable to wage pay, which impacts the overall cost the greatest. In summary, it would cost the carpet manufacturers approximately \$1.46 to reclaim and recycle 1 kg of N6. This is better than the current market price which is averaging around \$3.28 per kg-N6.

Table 8.34: Post Consumer Carpet for Nylon 6 Primary Material Reclamation - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg-recycled N6	% contribution
Fuel	$1,566,039	27.18¢	18.67%
Electricity	$807,487	14.01¢	9.63%
ENERGY TOTAL	$2,373,526	**41.19¢**	**28.30%**
Chemical Materials	$2,417,338	**41.95¢**	**28.83%**
Labor	$2,569,571	**44.59¢**	**30.64%**
Tipping	$1,025,500	17.80¢	12.23%
TOTAL	$8,385,935	**$1.46**	

Change Due to Collection Strategy

If the geographically dispersed collection scheme, outlined in Section 6.2.2.3, were employed instead of the generic estimates used for the base assessment, changes in the various impacts would occur in the rages outlined in Table 8.35. This collection scheme results in decreased impacts, which is undeniably beneficial in all categories except labor wages. However, there is a potential 23% total cost savings and environmental impact reductions ranging between 2-30%. The greatest environmental impact reduction is with the Smog Potential category, which is largely influenced by the collection process as discussed previously in this section.

Table 8.35: Percent of Impact Change due to Collection Scheme

Impact Category	% Change
Distance	-73%
Labor Wages	-43%
Collection Costs	-72%
Total Cost	-23%
Global Warming Potential	-15%
Human Health: Criteria Air Pollutants	-3%
Smog Potential	-31%
EcoToxicity	-2%

8.2.3 Secondary Material Reclamation

The scenarios discussed in this section refer to the open-loop recycling EOL activities for both the transformation of Nylon PCC-broadloom into carpet underlay and the recycling of N66 face fibers into glass reinforced plastic pellets. In the scenarios all of the PCC-broadloom is collected, yet only the portion that includes the recyclable materials is processed to separate the recyclable materials. Each scenario is first explored in terms of its annual impacts according to the average PIEs and the average higher-end collection scheme (refer to Chapter 6 Section 2 for more details on collection related assumptions and assessments). The effects of the PIE spread and the differences in annual miles traversed for collection are discussed in terms of deviation from the initial average impact assessments initially presented. The collection variances are individually discussed, while the variation due to PIEs is around ±17% unless otherwise noted.

8.2.3.1 Nylon Broadloom Face Fibers into Carpet Underlay

In this scenario, all of the PCC-broadloom is collected and transported to a recycling facility where it is size reduced and separated in order to recapture the Nylon (N6 and N66) face fibers from the backing. The remaining waste (backing materials, fillers, non-Nylon fibers etc.) is transported to the local landfill while the reclaimed Nylon is turned into carpet underlay. For a full description and diagram of the SMR-underlay EOL recycling scenario, refer to Section 3.5.

Environmental Impact

Most of the environmental impacts are dominated by the material separation phase. This is the main contributor to GWP, CAPs, and EcoToxicity. The main source of Smog Potential is the collection phase. However, another major contributor to the overall impact is the card+needlepunch phase. The energy required for this process causes impacts ranging from about 10-25% of the total environmental impacts reviewed.

Table 8.36: Carpet Underlay Secondary Material Reclamation - Individual Environmental Impact Categories

[g-pollutant]	pollutant	Collection	Bale	Shred	Grind	Separate	Card + Needlepunch	Landfill: transportation & disposal
GHGs	**CO_2**	3,824,452,000	50,311,000	1,408,704,000	1,383,548,000	5,961,836,000	3,295,562,000	72,678,000
	CH_4	24,400	0	0	0	0	0	460
	N_2O	24,400	0	0	0	0	0	4640
CAPs	**SO_2**	48,800	330,000	9,237,000	9,074,000	39,099,000	21,613,000	9280
	NO_x	23,738,000	61,500	1,722,000	1,692,000	7,290,000	4,030,000	451,000
	Pb	0	0	0	0	0	0	0
	CO	92,070,000	0	0	0	0	0	1,750,000
Additional Pollutants	**VOCs**	0	0	0	0	0	0	0
	Hg	0	1	27	26	114	63	0
	HC	7,717,000	0	0	0	0	0	147,000
	PM	586,000	0	0	0	0	0	11,100
	SO_x	0	0	0	0	0	0	0

Table 8.37: Carpet Underlay Secondary Material Reclamation - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Bale	Shred	Grind	Separate	Card + Needlepunch	Landfill: transportation & disposal
Global Warming Potential [CO_2 Equivalents]	CO_2	23.91%	0.31%	8.81%	8.65%	37.27%	20.60%	0.45%
	CH_4	98.14%	0.00%	0.00%	0.00%	0.00%	0.00%	1.86%
	N_2O	98.14%	0.00%	0.00%	0.00%	0.00%	0.00%	1.86%
	TOTAL	**23.94%**	**0.31%**	**8.80%**	**8.64%**	**37.25%**	**20.59%**	**0.46%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	0.06%	0.42%	11.63%	11.43%	49.24%	27.22%	0.00%
	NO_x	60.89%	0.16%	4.42%	4.34%	18.70%	10.34%	1.16%
	PM	98.14%	0.00%	0.00%	0.00%	0.00%	0.00%	1.86%
	TOTAL	**6.58%**	**0.39%**	**10.86%**	**10.67%**	**45.97%**	**25.41%**	**0.12%**
Smog Potential [NO_x Equivalents]	NO_x	60.89%	0.16%	4.42%	4.34%	18.70%	10.34%	1.16%
	HC	98.14%	0.00%	0.00%	0.00%	0.00%	0.00%	1.86%
	PM	98.14%	0.00%	0.00%	0.00%	0.00%	0.00%	1.86%
	TOTAL	**65.97%**	**0.14%**	**3.82%**	**3.75%**	**16.15%**	**8.93%**	**1.25%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	0.42%	11.64%	11.43%	49.27%	27.24%	0.00%
	Pb	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	CO	98.14%	0.00%	0.00%	0.00%	0.00%	0.00%	1.86%
	TOTAL	**6.44%**	**0.39%**	**10.88%**	**10.68%**	**46.04%**	**25.45%**	**0.12%**

Social Impact

The total annual labor potential of this EOL scenario amounts to nearly 200,000 hours. This roughly translates to 500 8-hr shifts per week or about 70 8-hr shifts per day. About 52% of this employment wage potential is attributable to transportation related activities. However, the actual recycling processes alone, the approximately 110,000 annual hour of labor corresponds to the potential for 260 8-hr shifts per week or 40 8-hr shifts per day. The largest employment wage potential based solely on the recycling process procedures is a result of the card+needlepunch process.

Table 8.38: Carpet Underlay Secondary Material Reclamation - Social Impact Categories

Process	Labor Hours	sec per kg-reclaimed Nylon	Labor Wages	cost per kg-reclaimed Nylon	% wage contribution
Collection	88,807	22.0	$1,474,188	10.03¢	52.43%
Bale	1,332	0.4	$15,712	0.11¢	0.56%
Shred	22,636	5.4	$149,510	1.02¢	5.32%
Grind	29,294	7.2	$386,968	2.63¢	13.76%
Separate	19,973	5.0	$299,194	2.04¢	10.64%
Card + Needlepunch	35,035	8.6	$458,259	3.12¢	16.30%
Transportation to Landfill	1,688	0.4	$28,015	0.19¢	1.00%
TOTAL	198,763	48.68	$2,811,845	19.13¢	

Economic Impact

The annual costs resulting from the SMR-underlay EOL scenario are around $6.2 million. 42% of this is a result of energy consumption, and approximately another 45% is attributable to wage pay, which is the single largest cost contributor. Wage pay is followed by fuel, which accounts for 25% of the overall costs. In summary, it would cost the carpet manufacturers approximately 42¢ to produce 1kg of carpet underlay from the recaptured PCC-broadloom. After the production of the recycled-content carpet underlay, the manufacturer could turn around and sell the underlay at the market rate of 95¢ per kg-underlay. This is a potential profit of around 53¢ per kg-underlay, which translates to estimated annual profit of nearly $7.8 million.

Table 8.39: Carpet Underlay Secondary Material Reclamation - Economic Impact (Costs Only)

Cost Category	Annual Impact	Annual Impact per kg-reclaimed Nylon	% contribution
Fuel	$1,555,770	10.58¢	25.10%
Electricity	$1,074,075	7.31¢	17.33%
ENERGY TOTAL	$2,629,844	17.89¢	42.42%
Labor	$2,811,845	19.13¢	45.36%
Tipping	$757,371	5.15¢	12.22%
TOTAL	$6,199,060	42.17¢	

Change Due to Collection Strategy

If the geographically dispersed collection scheme, outlined in Section 6.2.2.3, were utilized instead of the generic estimates used for the base assessment, changes in the various impacts would occur in the rages outlined in Table 8.40. This collection scheme results in decreased impacts, which is undeniably beneficial in all categories except labor wages. However, there is a potential 36% total cost savings and environmental impact reductions ranging between 30-40%.

Table 8.40: Percent of Impact Change due to Collection Scheme

Impact Category	% Change
Distance	-74%
Labor Wages	-39%
Collection Costs	-70%
Total Cost	-36%
Global Warming Potential	-33%
Human Health: Criteria Air Pollutants	-27%
Smog Potential	-39%
EcoToxicity	-27%

8.2.3.2 Nylon 6,6 Broadloom Face Fibers into Plastic Pellets

In this scenario, all of the PCC-broadloom is collected and transported to a recycling facility where it is size reduced and separated in order to recapture the N66 face fibers from the backing. The remaining waste (N6 carpet, backing materials, fillers, non-

Nylon fibers etc.) is transported to the local landfill while the reclaimed N66 is processed into glass reinforced plastic pellets for a future use in molded plastic parts. For a full description and diagram of the SMR-N66 EOL recycling scenario, refer to Section 3.5.

Environmental Impact

Most of the environmental impacts are dominated by the acquisition of the glass fibers used to reinforce the plastic pellets. This is the predominate contributor to GWP and EcoToxicity and a significant contributor to Smog Potential and CAPs. However, the main source of Smog Potential is again the collection phase, while the main source of CAPs is the material separation phase.

Table 8.41: Nylon 6,6 Secondary Material Reclamation - Individual Environmental Impact Categories

[g-pollutant]	pollutant	Collection	Bale	Shred	Grind	Separate	Glass Fibers	Pelletize	Landfill: transportation & disposal
GHGs	**CO_2**	3,824,452,000	50,312,000	1,408,726,000	1,383,570,000	5,961,931,000	5,301,461,000	132,507,000	31,739,00
	CH_4	24,400	0	0	0	0	56,700,000	0	200
	N_2O	24,400	0	0	0	0	0.00005	0	200
CAPs	**SO_2**	48,800	330,000	9,239,000	9,074,000	39,099,000	22,775,000	869,000	400
	NO_x	23,738,000	61,500	1,722,000	1,692,000	7,290,000	14,222,000	162,000	197,000
	Pb	0	0	0	0	0	90	0	0
	CO	92,070,000	0	0	0	0	4,300,000	0	764,000
Additional Pollutants	**VOCs**	0	0	0	0	0	190	0	0
	Hg	0	1	27	26	114	950	3	0
	HC	7,717,000	0	0	0	0	3,024,00	0	64,000
	PM	586,000	0	0	0	0	2,457,000	0	4,900
	SO_x	0	0	0	0	0	0	0	0

Table 8.42: Nylon 6,6 Secondary Material Reclamation - Environmental Equivalencies Impact Categories

[percentage impact]	pollutant	Collection	Bale	Shred	Grind	Separate	Glass Fibers	Pelletize	Landfill: transportation & disposal
Global Warming Potential [CO_2 Equivalents]	CO_2	21.14%	0.28%	7.79%	7.65%	32.95%	29.30%	0.73%	0.18%
	CH_4	0.04%	0.00%	0.00%	0.00%	0.00%	99.96%	0.00%	0.00%
	N_2O	99.18%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.82%
	TOTAL	**19.75%**	**0.26%**	**7.26%**	**7.13%**	**30.72%**	**34.04%**	**0.68%**	**0.16%**
Human Health: Criteria Air Pollutants [microDALYs]	SO_2	0.06%	0.41%	11.34%	11.14%	48.01%	27.97%	1.07%	0.00%
	NO_x	48.36%	0.13%	3.51%	3.45%	14.85%	28.98%	0.33%	0.40%
	PM	19.23%	0.00%	0.00%	0.00%	0.00%	80.61%	0.00%	0.16%
	TOTAL	**5.80%**	**0.34%**	**9.58%**	**9.41%**	**40.54%**	**33.38%**	**0.90%**	**0.05%**
Smog Potential [NO_x Equivalents]	NO_x	48.36%	0.13%	3.51%	3.45%	14.85%	28.98%	0.33%	0.40%
	HC	71.42%	0.00%	0.00%	0.00%	0.00%	27.99%	0.00%	0.59%
	PM	19.23%	0.00%	0.00%	0.00%	0.00%	80.61%	0.00%	0.16%
	TOTAL	**51.68%**	**0.11%**	**2.99%**	**2.94%**	**12.65%**	**28.93%**	**0.28%**	**0.43%**
EcoToxicity [g 2,4-D Equivalents]	Hg	0.00%	0.09%	2.41%	2.36%	10.19%	84.73%	0.23%	0.00%
	Pb	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
	CO	94.79%	0.00%	0.00%	0.00%	0.00%	4.43%	0.00%	0.79%
	TOTAL	**1.40%**	**0.08%**	**2.37%**	**2.33%**	**10.04%**	**83.54%**	**0.22%**	**0.01%**

Social Impact

The total annual labor potential of this EOL scenario amounts to nearly 164,000 hours. This roughly translates to 400 8-hr shifts per week or about 55 8-hr shifts per day. About 58% of this employment wage potential is attributable to transportation related activities. However, the actual recycling processes alone, creates approximately 74,000 annual hour of labor corresponding to the potential for 175 8-hr shifts per week or 25 8-hr shifts per day. And, the largest employment wage potential based solely on the recycling process procedures is a result of the material grinding process.

Table 8.43: Nylon 6,6 Secondary Material Reclamation - Social Impact Categories

Process	Labor Hours	sec per kg-reclaimed N66	Labor Wages	Labor cost per kg-reclaimed N66	% wage contribution
Collection	88,807	29.00	$1,474,188	13.37¢	58.21%
Bale	1,332	0.43	$52,698	0.48¢	2.08%
Shred	22,636	7.39	$299,020	2.71¢	11.81%
Grind	29,294	9.56	$386,968	3.51¢	15.28%
Separate	19,973	6.52	$299,194	2.71¢	11.81%
Pelletize	613	0.20	$8,441	0.08¢	0.33%
Transportation to Landfill	737	0.24	$12,234	0.11¢	0.48%
TOTAL	163,390	53.37	$2,532,743	22.97¢	

Economic Impact

The annual costs resulting from the SMR-N66 EOL scenario are around $23 million. 75% of this is associated with the purchasing of the glass fibers. Only 11% of the overall costs are attributable to wage pay; this is closely followed by energy consumptions where fuel accounts for 7% and electricity for 3% of the total costs. In summary, it would cost the carpet manufacturers approximately $1.48 to produce 1kg of glass reinforced N66 plastic pellets from the recaptured PCC-broadloom (assuming a ratio of 7:3 nylon to glass). After the production of the recycled-content plastic pellets, the manufacturer could turn around and sell the pellets at the market rate of $3.68 per kg-glass reinforced N66 pellets. This is a potential profit of around $2.20 per kg-plastic pellet, which translates to estimated annual profit of nearly $35 million.

Table 8.44: Nylon 6,6 Secondary Material Reclamation - Economic Impact

Cost Category	Annual Impact	Annual Impact per kg-reclaimed Nylon	% contribution
Fuel	$1,539,426	13.96¢	6.63%
Electricity	$793,300	7.20¢	3.42%
ENERGY TOTAL	$2,332,726	21.16¢	10.05%
Labor	$2,532,743	22.97¢	10.91%
Virgin Materials	$17,482,536	$1.59	75.31%
Tipping	$867,621	7.87¢	3.74%
TOTAL	$23,215,626	$2.11	

Change Due to Collection Strategy

If the geographically dispersed collection scheme, outlined in Section 6.2.2.3, were utilized instead of the generic estimates used for the base assessment, changes in the various impacts would occur in the rages outlined in Table 8.45. This collection scheme results in decreased impacts, which is undeniably beneficial in all categories except labor wages, which decrease here by 44%. However, there is only a potential 8% total cost savings and environmental impact reductions ranging between 1-25%. This low percentage changes in impact are due in large part because the acquisition of glass fibers for the recycling process dominates both the environmental and economic impacts of the overall SMR-N66 EOL scenario.

Table 8.45: Percent of Impact Change due to Collection Scheme

Impact Category	% Change
Distance	-75%
Labor Wages	-44%
Collection Costs	-61%
Total Cost	-8%
Global Warming Potential	-11%
Human Health: Criteria Air Pollutants	-3%
Smog Potential	-24%
EcoToxicity	-1%

CHAPTER 9

POST-CONSUMER CARPET END-OF-LIFE COMPARATVIE ASSESSMENT

9.1 Post Consumer Carpet-Tile EOL Scenarios

9.1.1 Disposal versus PVC Primary Material Reclamation

The comparative assessment for the PCC-tile EOL scenarios is between the landfill scenario and the PMR-PVC, which includes the closed-loop recycling of the PVC backing materials in carpet tiles. Table 9.1 contains the percent differences in the various impact categories between the baseline landfill scenario and the PMR-PVC scenario. All of the impact categories suggest that the PMC-PVC scenario is the preferred EOL options of the PCC-tile materials. The economic savings is around 77% while the employment potential is around 780% per year. The environmental savings range from 50% to nearly 75% with the alternative EOL scenario. In order to better understand these recommendations though, the tipping points for the various impact categories are explored and summarized in Table 9.2.

Table 9.1: PVC Landfill vs. PMR Comparative Impacts

	Impact Category	% Difference
Social Impact	Labor Hours	860%
	Labor Wages	780%
Economic Impact	Total Costs	-77%
Environmental Impact	Global Warming Potential	-53%
	Human Health: Criteria Air Pollutants	-72%
	Smog Potential	-63%
	EcoToxicity	-49%

The numbers in Table 9.1 suggest that under the generalized assumptions, there is the potential for realization of benefits in all impact categories. Thus, the recommended alternative is the PMR-PVC scenario. Factors that would reverse the EOL waste management recommendation include the cost of virgin PVC materials, process efficiencies, and percentage of recyclable material per kg PCC-tile collected. First, if every other factor remained the same, and only the price of virgin PVC was changed, a price decrease of 56% would be needed in order to economically reverse the recommendation. However, the environmental improvements of the PMR-PVC scenario would still far outweigh the impacts of the Landfill scenario. The landfill scenario would have to see environmental reduction in collection strategies and manufacturing practices of viring materials average anywhere from 50% to 75% in order to reverse the recommendation in favor of WD.

Table 9.2: Sensitivity of Landfill vs. PMR-PVC Recommendations

		Recommendations					
Parameter	**% change**	**Social**	**Economic**	**Environmental**			
				GWP	CAPs	Smog	EcoToxicity
Baseline Comparison	0%	PMR	PMR	PMR	PMR	PMR	PMR
Cost of Virgin PVC	-86%	PMR	L	PMR	PMR	PMR	PMR
WD: GWP	-53%	PMR	PMR	L	PMR	PMR	PMR
WD: CAPs	-72%	PMR	PMR	PMR	L	PMR	PMR
WD: Smog	-63%	PMR	PMR	PMR	PMR	L	PMR
WD: EcoTox	-49%	PMR	PMR	PMR	PMR	PMR	L

9.2 Post Consumer Carpet-Broadloom EOL Scenarios

9.2.1 Disposal versus Repurpose Material Reclamation

The comparative assessment for the PCC-broadloom EOL scenarios is between the landfill scenario and the RMR, which includes the repurposing of nylon broadloom carpet offered as a charitable donation for its second life. Table 9.3 contains the percent differences in the various impact categories between two baseline landfill scenarios, which differ in the replacement of the repurposed broadloom carpet with virgin nylon carpet, and the RMR scenario. Based on the percentages presented in the table, the EOL recommendation for the case without replacement is clearly to dispose of the PCC-broadloom in the local landfills throughout the Atlanta metropolitan region. This recommendation is predictable, given the fact that energy and materials lead to costs and emissions that are not recouped by donating the carpet. However, for the EOL scenario which includes replacement, the RMR scenario is clearly the preferred alternative. So, assuming the carpet manufacturing was to donate carpet regardless of its source, the preferred method would be through repurposed carpet as opposed to manufacturing and donating carpet from virgin materials. Because only good-quality PCC-broadloom that is disposed of before the end of its useful primary life is even considered for repurposing, the RMR would produce nearly-new carpet comparable to the brand-new carpet. Thus, the RMR with material replacement is a viable EOL scenario and will be considered the preferred scenario for further comparative assessments. However, if some improvements were to be made to the baseline landfill scenario, it could possibly lead to landfill EOL scenario preferences. The sensitivity of these recommendations for RMR scenarios is discussed after Table 9.3.

Table 9.3: PCC-broadloom Landfill vs. RMR Comparative Impacts

	Impact Category	% Difference (w/o replacement)	% Difference (w/ replacement)
Social Impact	Labor Hours	610%	610%
	Labor Wages	547%	547%
Economic Impact	Total Costs	96%	-96%
Environmental Impact	Global Warming Potential	948%	-97%
	Human Health: Criteria Air Pollutants	3815%	-98%
	Smog Potential	534%	-96%
	EcoToxicity	2701%	-96%

The percent differences in Table 9.3 for the scenario which includes the replacement of nylon broadloom carpet, suggest that under the generalized assumptions, there is a preference in all three impact categories for the RMR scenario. The differences range from nearly 100% improvements in environmental impacts to nearly 550% more labor wage potential in the RMR scenario.

Factors that would reverse the EOL waste management recommendation in favor of the landfill scenario include the economic and environmental costs of manufacturing virgin nylon broadloom carpets and the percentage of repurpose-able PCC-broadloom out of all of the PCC collected. First, if the percentage of repurpose-able nylon broadloom carpet were reduced from 80% to 0.5% of the PCC-broadloom collected (around 160,000kg repurpose-able PCC-broadloom per year), while the remaining factors remained unchanged, the baseline landfill scenario, which includes the replacement of repurpose-able nylon broadloom, would still be preferred in four out of the six impact categories as listed in Table 9.4. In order to reverse the recommendation based on the price of new nylon broadloom carpet, the market price would have to be reduced from $7.94 per kg to about 4¢ per kg (a reduction of 99.5%). This reduction in price is impractical; thus it can be effectively asserted that the price of new nylon carpet does not play a significant role in the comparative assessment of repurpose-able PCC-broadloom.

Table 9.4: Sensitivity of Landfill vs. PCC-broadloom RMR Recommendations

		Recommendations					
Parameter	**% change**	**Social**	**Economic**	**Environmental**			
				GWP	CAPs	Smog	EcoToxicity
Baseline Comparison	0%	RMR	RMR	RMR	RMR	RMR	RMR
Repurpose-able PCC-broadloom	-99.5%	RMR	L	L	RMR	L	L
Price of Nylon Broadloom	-99%	RMR	L	RMR	RMR	RMR	RMR

9.2.2 Disposal versus N6 Primary Material Reclamation

This PMR-N6 comparative assessment between the N6 face fibers of PCC-broadloom, which includes the closed-loop recycling of N6 into pellets of its original monomer to be extruded into fibers for use in new broadloom carpet, and the baseline landfill scenario that encompasses the acquisition of virgin nylon pellets in equal amounts to those disposed. Table 9.5 contains the percent differences in the various impact categories between the baseline landfill scenario and PMR-N6 scenario. Based on the percentages presented in the table, the EOL recommendation for the N6 face fibers of PCC-broadloom is the PMR-N6 scenario. The overwhelming amount of support for the PMR-N6 scenario only serves to further stress the impacts associated with using virgin materials in product production. Even though the energy requirements of the recycling process are intense and the depolymerization process itself requires the assistance of a catalyst, these inputs do not even compare to the environmental impacts associated with the virgin N6 materials.

Table 9.5: PCC-broadloom Landfill vs. PMR-N6 Comparative Impacts

	Impact Category	% Difference
Social Impact	Labor Hours	923%
	Labor Wages	848%
Economic Impact	Total Costs	-57%
Environmental Impact	Global Warming Potential	-74%
	Human Health: Criteria Air Pollutants	-53%
	Smog Potential	-65%
	EcoToxicity	-2%

Even though this baseline comparison supports the argument for PMR-N6 in all impact categories considered, in order to better understand the sensitivity associated with the recommendation, it is import to determine the factors that would tip the impact scales in favor of disposal. There is a potential to alter the recommendation in all categories except social impact; the stability of the social impact recommendation is inherent in the scope of the scenario, which is outlined in Section 3.4. The only employment potential in the baseline landfill scenario is in the collection and transportation of the PCC to the local landfills; this same employment potential, plus the additional labor required by the recycling activities themselves, is present in the PMR-N6 scenario. Therefore, regardless of the changes to the PMR scenario, the employment potential will always be greater than the baseline. The next impact category to consider is the economic impact. This impact category generally drives most business decisions, thus it is important to fully understand the sensitivity of the recommendation in this particular category. The primary cost players in both EOL scenarios are the prices of virgin N6 monomer in the landfill scenario and the energy costs, primarily fuel, material costs associated with the acquisition of the chemical catalyst, and labor wages in the PMR-N6 EOL scenario. The PMR-N6 EOL scenario would have to witness a 310% total cost increase in order to become the unfavorable economic alternative. This would be possible if there was an

850% increase in the market prices of the catalyst, which would drive the material costs of the depolymerization process to nearly \$3.50 per kg-recyclable N6. Conversely, if the price of virgin materials in the landfill scenario drops 63%, the landfill scenario would be the recommended EOL option based on its lower economic impact. However, considering the trends of virgin materials in the market, they are more likely to rise than to fall. Therefore based on economic impacts, it would appear that under no practical circumstances would the landfill scenario be the preferred EOL scenario for the PCC-broadloom when compared to the PMR-N6 EOL scenario.

Table 9.6: Sensitivity of Landfill vs. PMR-N6 Recommendations

		Recommendations					
Parameter	**% change**	**Social**	**Economic**	**Environmental**			
				GWP	CAPs	Smog	EcoToxicity
Baseline Comparison	0%	PMR	PMR	PMR	PMR	PMR	PMR
Total Cost – PMR	310%	PMR	L	PMR	PMR	PMR	PMR
Price of Catalyst	850%	PMR	L	PMR	PMR	PMR	PMR
Price of Virgin N6	-63%	PMR	L	PMR	PMR	PMR	PMR
GW Collection – PMR	0%	PMR	PMR	PMR	PMR	PMR	PMR

9.2.3 Disposal versus Nylon Secondary Material Reclamation – Carpet Underlay

The comparative assessment for the PCC-broadloom EOL scenarios is between the baseline landfill scenario and the SMR-underlay in which Nylon face fibers are recycled into carpet underlay; this is an open-loop recycling process. Table 9.7 contains the percent differences in the various impact categories for comparative assessments between the two baseline landfill scenarios and the SMR-underlay scenario. The baseline landfill scenarios differ in the environmental impacts associated with the manufacturing of virgin carpet underlay. The landfill scenario without material replacement includes only the collection of PCC-broadloom and its transportation to local landfills. The second landfill scenario includes, in addition to the collection and transportation of PCC-broadloom, the environmental impacts associated with the manufacturing of virgin underlay. This comparison is included in order to better grasp the more global comparative environmental impacts between the manufacturing of products from virgin materials and from recycled content materials. This difference in the two landfill scenarios is only realized in the environmental impact categories, the social and economic impacts remain unchanged. According to the percentages presented in the table, the EOL recommendation based on environmental impacts is inconclusive for the scenario with underlay replacement but is strongly supportive of the landfill scenario for the scenario without replacement. If taking the perspective of the manufacturer, the social and economic impacts would suggest the SMR-underlay scenario. Unfortunately, the more narrowed view of the environmental impacts between the two assessments supports landfilling. However, if taking a more global perspective on the environmental impacts, the environmental preference is less definitive. The CAPs and Smog Potential impacts support the SMR-underlay scenario while the GWP and EcoToxicity support the landfill scenario, albeit at relatively low differences. Taking this comparative assessment further, the comparison which includes the replacement of carpet underlay in the landfill scenario, the sensitivity of the recommendations will be explored in order to determine the process improvements and circumstance needed in order to definitively offer a suggestion for the management of PCC-broadloom in the context of SMR-underlay. This discussion follows Table 9.7.

Table 9.7: PCC-broadloom Landfill vs. SMR-underlay Comparative Impacts

	Impact Category	% Difference (w/o replacement)	% Difference (w/ replacement)
Social Impact	Labor Hours	1,118%	1,118%
	Labor Wages	938%	938%
Economic Impact	Total Costs	-485%	-485%
Environmental Impact	Global Warming Potential	2,172%	9%
	Human Health: Criteria Air Pollutants	8,054%	-37%
	Smog Potential	725%	-17%
	EcoToxicity	8,559%	60%

Because there is no definitive EOL preference based on the results presented in Table 9.7, it is important to determine what changes would need to occur before an absolute recommendation could be made. The social impact categories are likely to remain unchanged regardless of alterations to process efficiencies due in part to the way the labor hours and wages are generated. The social impact categories represent potential employment opportunities, thus the landfill scenario only creates jobs in the transportation section of the scenario where the PCC-broadloom is collected and transported to the local landfills while the SMR-underlay scenario includes all of the labor required for processing in addition to the labor required for collection. Therefore, the labor potential for the SMR-underlay scenario will always be greater than the labor potential for the landfill scenario. This leaves the determining factors up to economic and environmental impacts. Therefore, if the economic impact sways towards the landfill scenario, the recommendation would likely sway in that direction as well. Conversely, if the environmental impacts for the SMR-underlay scenario could be decreased through increased process or collection efficiencies, then the EOL recommendation would definitively sway towards the SMR-underlay EOL option. These two categories are explored below and the results are found in Table 9.8.

The exploration of changes to costs incurred during the landfill scenario is discussed first. The current scenario, however, strongly support the SMR-underlay scenario because the per unit costs of recycling the material is less than the current price of carpet underlay on the market today. Therefore, in order for the scales to tip in favor of the landfill scenario, the costs of manufacturing the virgin underlay would have to drop somewhere in the range of 70%.

The other alternatives explored for creating a definitive recommendation revolve around the environmental impacts associated with the SMR-underlay scenario. The major process contributors to the negative environmental impacts of the EOL scenario are (in descending order of percentage impact) material separation, collection, shredding, grinding, card+needlepunch, baling, and lastly transportation to landfill. This order suggests that there is the most room for improvement within the material separation and collection phases. As a starting point, a 38% decrease in environmental impacts would have to be reached in order to favor the SMR-underlay EOL scenario in all environmental impact categories. At this reduction, all environmental impact categories would favor the SMR-underlay scenario. However, each environmental impact category tips at various points. At a 9% reduction in GWP and a 38% reduction in EcoToxicity would tip each individual impact category in the direction of the SMR-underlay scenario. One way to achieve this improved environmental performance in the SMR-underlay scenario is through increased efficiency of the collection process. Taking the lower bound of the collection scheme, the Goodwill collection scenario discussed in Sections 6.2.2.3 and

6.2.3, the SMR-underlay EOL scenario becomes the preferred scenario in all categories except EcoToxicity, where the landfill scenario is still preferred by a 16% difference. This remaining environmental impact category favoring the landfill scenario is most influenced by the separation process; therefore, it will be necessary to improve the efficiency of this process in order to solidify the SMR-underlay recommendation. It would require an 82% improvement in the separation process alone to definitively sway the recommendation in complete favor of the SMR-underlay scenario. An efficiency increase of 82% is a little steep; therefore, a combination of process improvements would likely be needed in order to solidify an EOL recommendation in this comparative assessment between landfilling and a SMR-underlay scenario including an open-loop recycling process converting nylon face fibers into carpet underlay.

Table 9.8: Sensitivity of Landfill vs. PCC-broadloom SMR-underlay Recommendations

		Recommendations					
Parameter	% change	Social	Economic	Environmental			
				GWP	CAPs	Smog	EcoToxicity
Baseline Comparison	0%	SMR	SMR	L	SMR	SMR	L
Price Virgin Underlay	-70%	SMR	L	L	SMR	SMR	L
Environmental Impact – SMR-underlay	-38%	SMR	SMR	SMR	SMR	SMR	SMR
Goodwill Collection Estimate[10]	-73%	SMR	SMR	SMR	SMR	SMR	L
Separation Energy Consumption	-82%	SMR	SMR	SMR	SMR	SMR	SMR

9.2.4 Disposal versus N6,6 Secondary Material Reclamation

This comparative assessment for the PCC-broadloom EOL scenarios is between two landfill scenarios and the SMR-N66 EOL option, which includes the processing of N66 face fibers into glass reinforced plastic pellets for sale in an outside industry. Table 9.9 contains the percent differences in the various impact categories between two

[10] No actual change was made to the Lower Estimate for the PCC-broadloom collection scheme. The lower collection scheme estimate was used to estimate the impacts of the SMR-underlay scenario in order to assess the difference between the recycling and landfill scenarios for the PCC-broadloom.

baseline landfill scenarios, which differ only in the inclusion of the environmental impacts associated with the acquisition of virgin glass reinforced plastic N66 pellets equal in weight to what could have been manufactured from the recyclable N66 face fibers, and the SMR-N66 scenario. Based on the percentages presented in the table, the EOL environmental recommendation for the case without replacement is clearly to dispose of the PCC-broadloom in the local landfills throughout the Atlanta metropolitan region; however, the economic and social impacts favor the SMR-N66 scenario. For the EOL scenario which includes replacement, the SMR-N66 scenario is the preferred alternative in all but the EcoToxicity environmental impact, which is heavily influenced by the impacts associated with the glass fibers. So, assuming the more global environmental perspective associated with the second comparative assessment, the preferred EOL management practice is the SMR-N6 scenario. However, in order to build confidence in this recommendation, it is necessary to explore the sensitivity of the impacts and determine the tipping points that would change the results. The sensitivity of these recommendations for the SMR-N66 scenarios is discussed after Table 9.3.

Table 9.9: PCC-broadloom Landfill vs. SMR-N66 Comparative Impacts

	Impact Category	% Difference (w/o replacement)	% Difference (w/ replacement)
Social Impact	Labor Hours	90%	90%
	Labor Wages	89%	89%
Economic Impact	Total Costs	-106%	-106%
Environmental Impact	Global Warming Potential	96%	-628%
	Human Health: Criteria Air Pollutants	99%	-488%
	Smog Potential	91%	-522%
	EcoToxicity	100%	85%

The percent differences in Table 9.9 for the second assessment, which includes the acquisition of virgin plastic pellets, suggest that under the generalized assumptions, there is a preference in all three impact categories for the SMR-N66 scenario. The differences range from 90% improvements in social impacts to a little over 100% improvements in overall economic impacts and around 500% and more in environmental improvements. The only category that shows preferences for the landfill scenario is the EcoToxicity environmental category; this preference is due to the environmental burdens associated with the acquisition of the glass fibers necessary for the processing of the reinforced plastic pellets from the reclaimed N66 fibers.

Factors that could reverse the EOL waste management recommendation in favor of the landfill scenario include the market price of the virgin plastic pellets and the environmental impacts associated with the manufacturing of the pellets, both virgin and recycled. First, if the market prices of the pellets dropped 60%, the landfill scenario would turn out to be the preferred management scenario if the recommendation only took into account the economic impacts. However, in order to reverse the recommendation in the context of environmental impacts, emissions reductions of over 90% in the GWP, CAPs, and Smog Potential categories would have to occur in the manufacturing of virgin pellets in order to make the landfill scenario the more attractive alternative. For a definitive SMR-N66 recommendation, however, the EcoToxicity indicator would have to see a 95% reduction either through process efficiencies or improvements in the manufacturing and acquisition of glass fibers.

Table 9.10: Sensitivity of Landfill vs. SMR-N66 Recommendations

		Recommendations					
Parameter	**% change**	**Social**	**Economic**	**Environmental**			
				GWP	CAPs	Smog	EcoToxicity
Baseline Comparison	0%	SMR	SMR	SMR	SMR	SMR	L
Mkt Price Pellets	-60%	SMR	L	SMR	SMR	SMR	L
Landfill: GWP	-97%	SMR	SMR	L	SMR	SMR	SMR
Landfill: CAPs	-93%	SMR	SMR	SMR	L	SMR	L
Landfill: Smog	-94%	SMR	SMR	SMR	SMR	L	L
SMR-N66: EcoToxicity	-95%	SMR	SMR	SMR	SMR	SMR	SMR

9.3 Comparative Assessment Sensitivities Explored

Several assumptions have been made regarding specificity of input data and process efficiencies. Consequently, these assumptions have a direct input on the comparative assessments and recommendations made and discussed in Sections 9.1 and 9.2. In this section, some of these assumptions will be explored so that their impacts can be understood in greater detail. First, the process efficiencies used to determine the electricity requirements of the mechanical and chemical recycling activities will be varied, and second, the impact of localized data will be tested.

9.3.1 Process Efficiencies

The initial assumption in this study regarding process efficiencies and motor loads for the mechanical and chemical processes was set at 100% as a simple way to assess the impact of the process chain on the overall EOL network and to establish a baseline estimate. However, because a large part of the overall impact comes from these individual processes, like the separation process or the card+needlepunch process, it will be beneficial to explore the impact of efficiency variance on the overall EOL recommendation.

The following equation, first introduced in Section 7.1.1, is used to calculate the electricity required to process 1kg of material.

$$M_i \times 0.746\left[\frac{kW}{hp}\right] \times \frac{1}{T_i} \times LF \times \frac{1}{eff}$$

Equation 7

To explore the inverse effects of efficiency on overall environmental impact, this test will vary the efficiency of a particular process, generally the process with the greatest percentage of environmental impact on a given EOL scenario, from 25% to 100%. The results of the sensitivity test for each comparative study are discussed below.

9.3.1.1 Primary Material Reclamation – Polyvinyl Chloride: Material Separation

The effects of the material separation process on the EOL recommendations are explored for the PMR-PVC scenario. The following four graphs, found in Figures Figure 9.1 through Figure 9.4, demonstrate the impact of the separation process efficiency on the environmental recommendation for the waste management of PCC-tile. In both the CAPs and Smog Potential categories, the efficiency of the process does not appear to ultimately change the EOL recommendation. In both of these categories, it is always preferable to recycle than to landfill the materials. However, in the GWP and EcoToxicity categories, at about 30% - 40% process efficiency range, the ultimate EOL preferences for these two environmental categories switches from PMR to WD. Therefore, in order to maintain an environmental preference for the PMR-PVC EOL options, separation efficiency greater than 40% would have to be maintained.

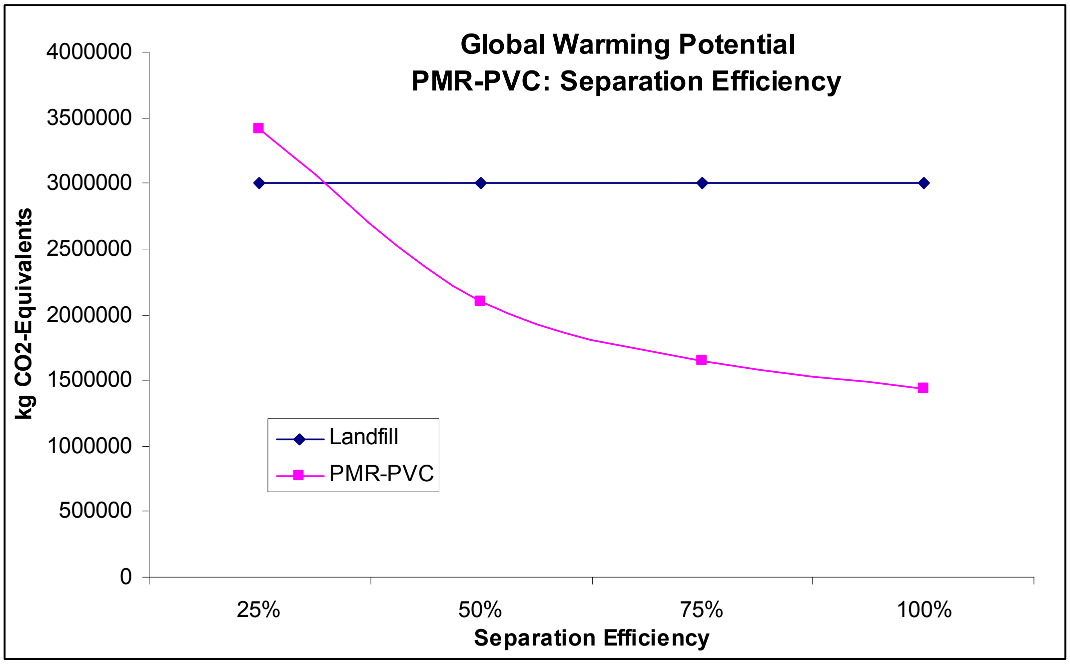

Figure 9.1: Effect of Separation Efficiency on Global Warming Potential

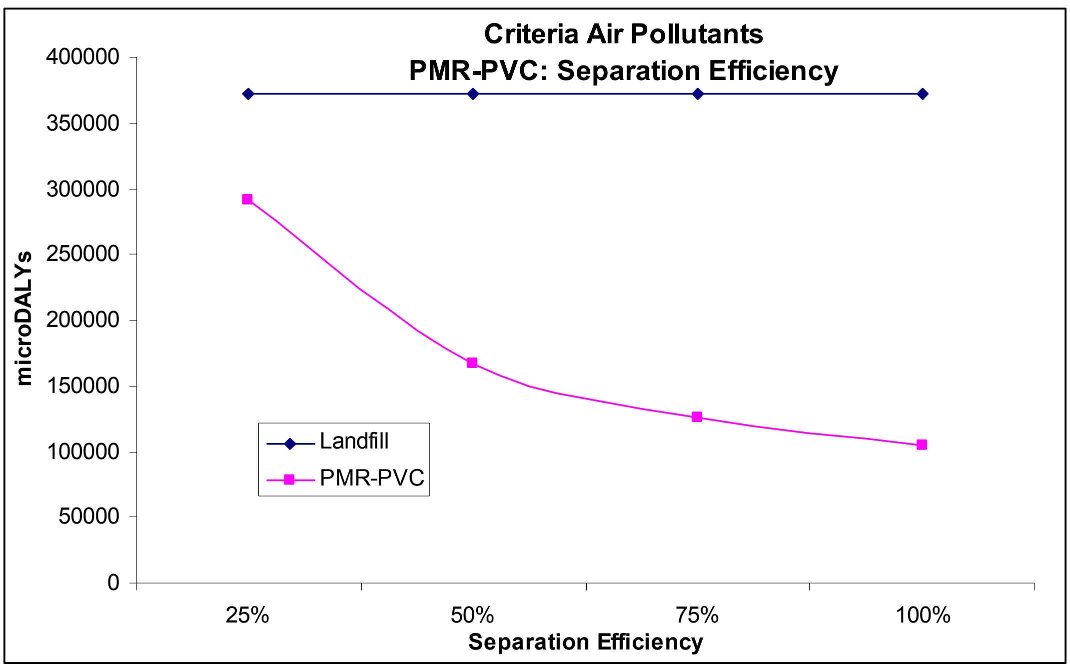

Figure 9.2: Effect of Separation Efficiency on Criteria Air Pollutants

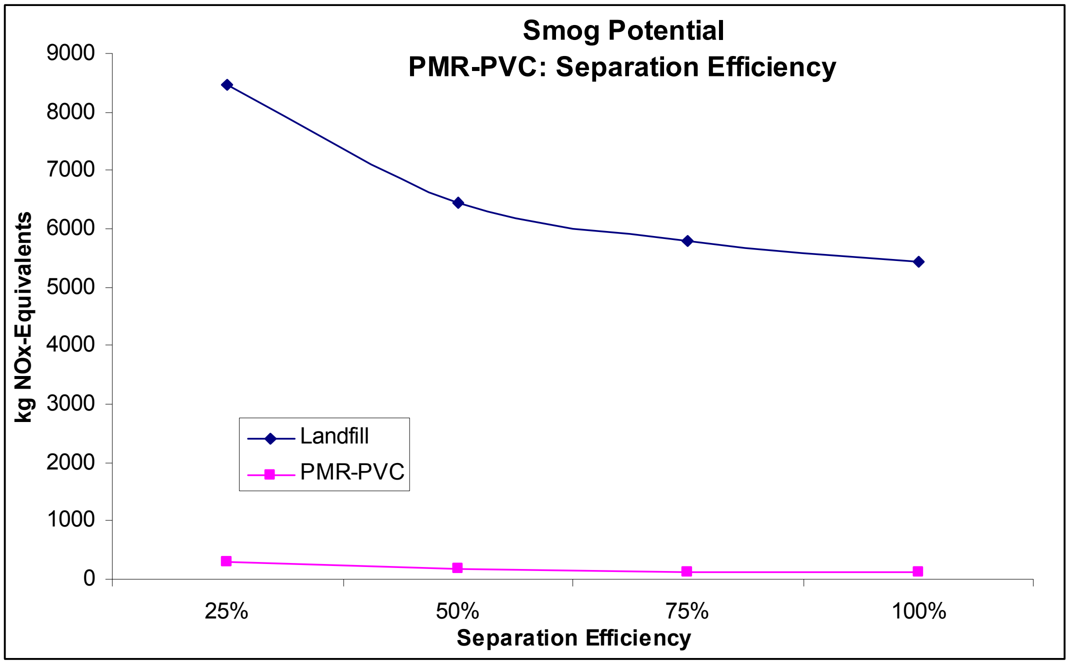

Figure 9.3: Effect of Separation Efficiency on Smog Potential

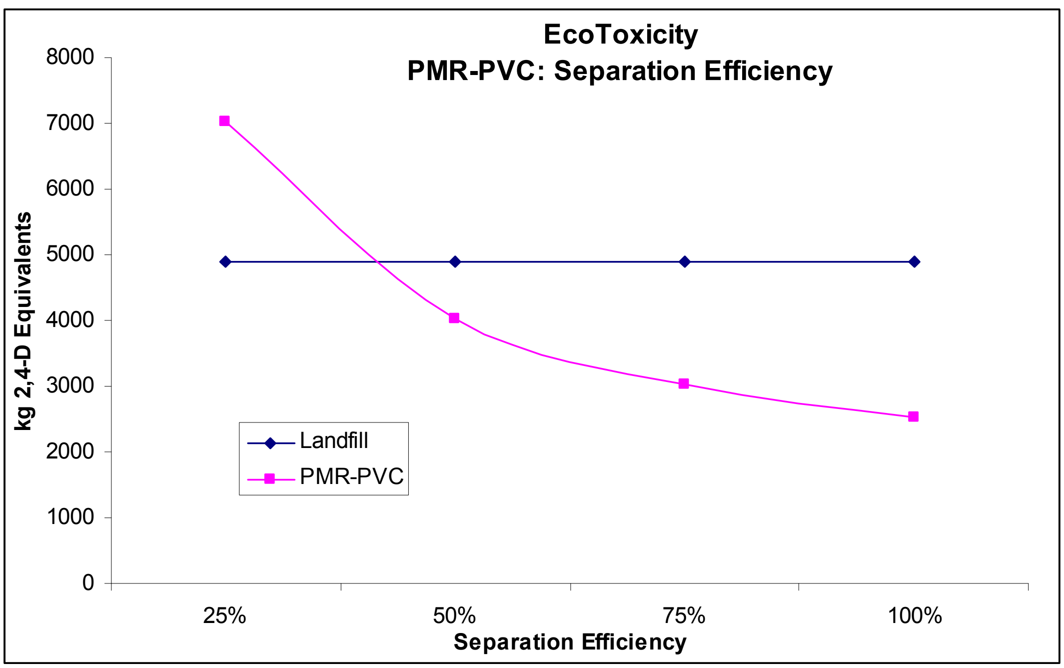

Figure 9.4: Effect of Separation Efficiency on EcoToxicity

9.3.1.2 Primary Material Reclamation – Nylon 6: Reactor and Material Separation

The effects of the material separation process on the EOL recommendations are explored for the PMR-N6 scenario. The following four graphs, found in Figure 9.5

through Figure 9.8, demonstrate the impact of the separation and reactor process efficiencies on the environmental recommendation for the waste management of PCC-broadloom N6 materials. In all four environmental categories, the efficiency of the reactor appears to have to impact of the recommendation; the PMR-N6 option is always preferred. However, variations in the efficiency of the separation process do have an impact on the recommendation based in these environmental criteria. Both the CAPs and EcoToxicity categories are impacted by the efficiency of the separation process. In order to maintain the preferences for the alternative EOL options, the separation process must have an efficiency greater than 50%.

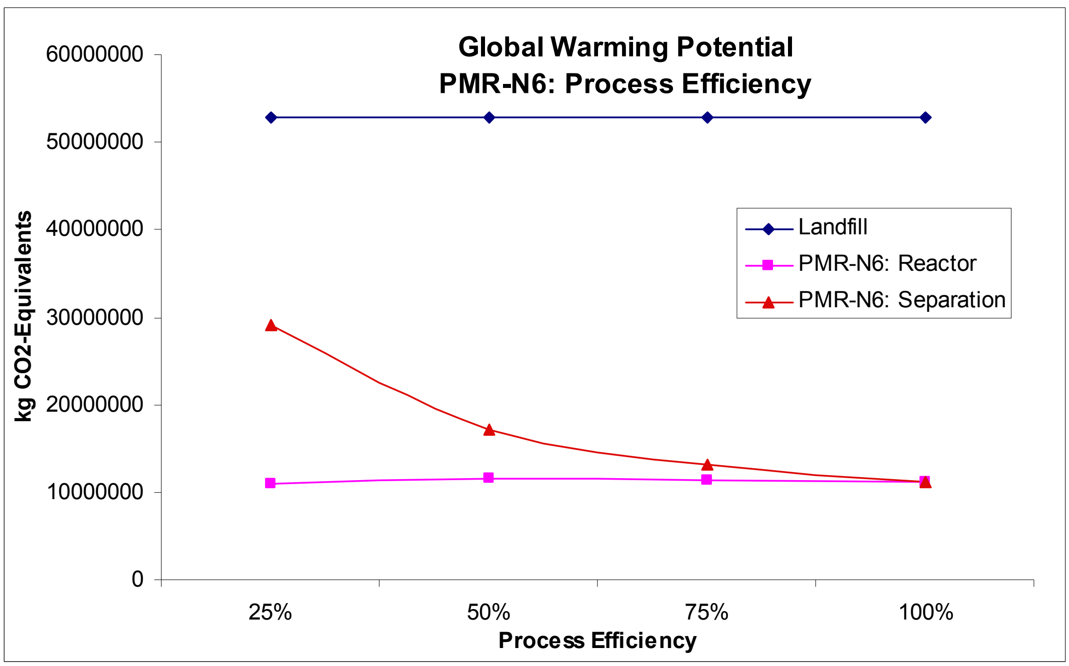

Figure 9.5: Effect of Separation & Reactor Efficiency on Global Warming Potential

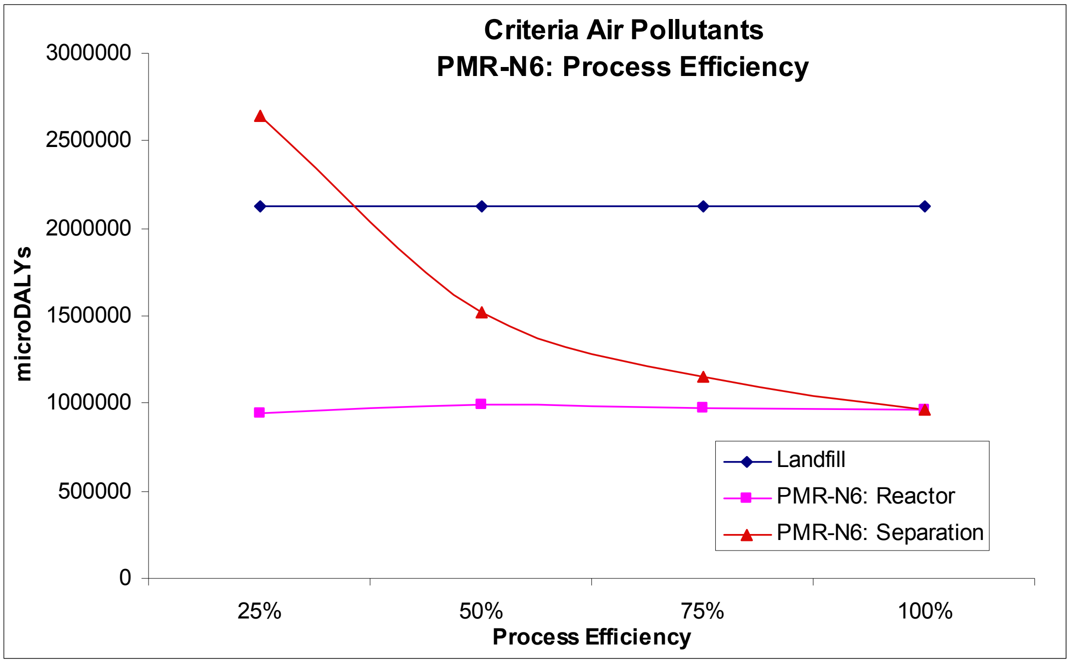

Figure 9.6: Effect of Separation & Reactor Efficiency on Criteria Air Pollutants

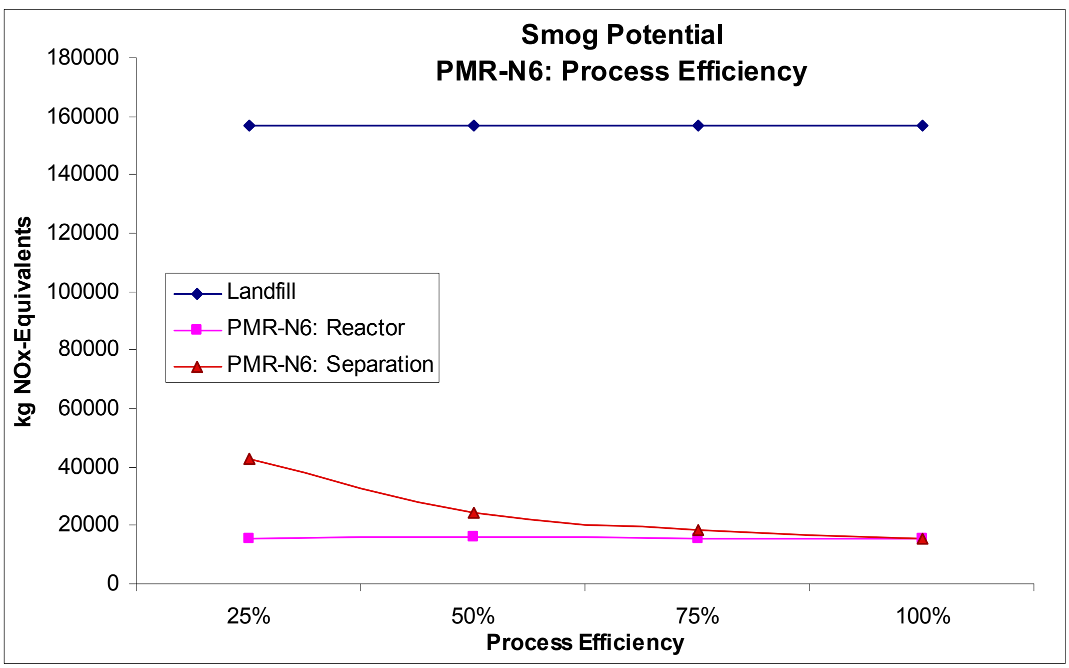

Figure 9.7: Effect of Separation & Reactor Efficiency on Smog Potential

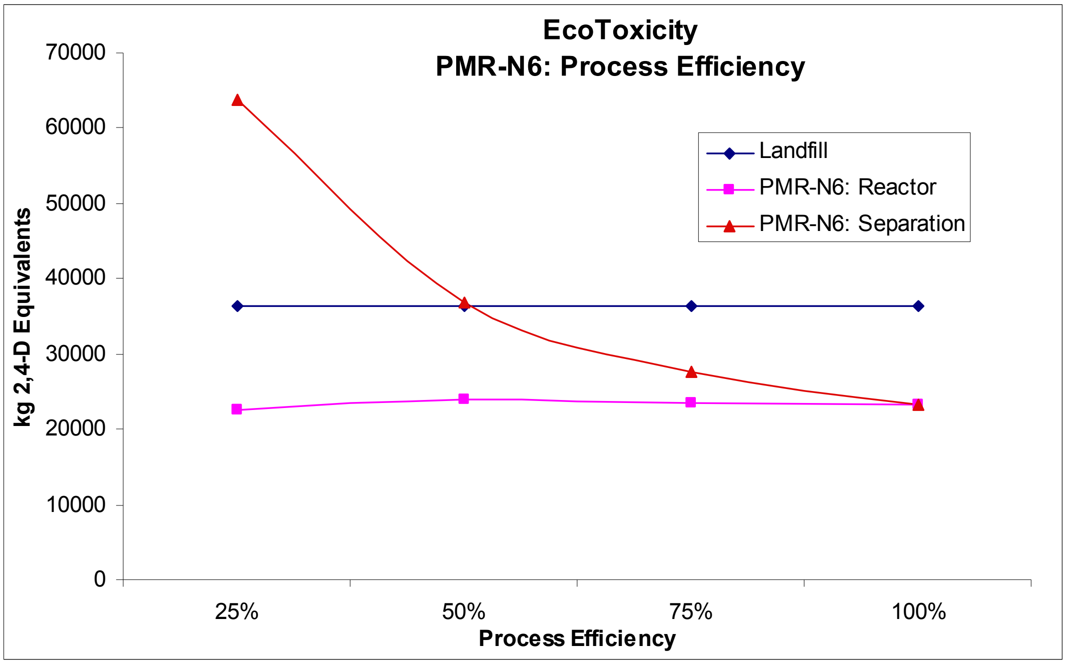

Figure 9.8: Effect of Separation & Reactor Efficiency on EcoToxicity

9.3.1.3 Secondary Material Reclamation – Underlay: Card+Needlepunch

The effects of the carding and needelpunch processes on the EOL recommendations are explored for the SMR-underlay scenario. The following four graphs, found in Figure 9.9 through Figure 9.12, demonstrate the impact of the carding and needlepunch process efficiencies on the environmental recommendation for the waste management of PCC-broadloom nylon materials. In this case, it appears that the efficiency of the carding and needlepunch processes do impact the EOL recommendation based on the environmental indicators. For GWP, an efficiency of 50% or greater must be maintained in order the waste management preference to favor the SMR-underlay scenario. With regards to the CAPs criteria, it appears that there isn't much room for decreased efficiency after about 25% for the SMR-underlay scenario to be recommended; the same suggestion goes to Smog Potential as well. Unfortunately, it does appear that the SMR-underlay scenario is not the preferred option under the EcoToxicity criteria regardless of the process efficiency. However, the differences do narrow quite a bit as the card+needlepunch efficiency approaches 100%.

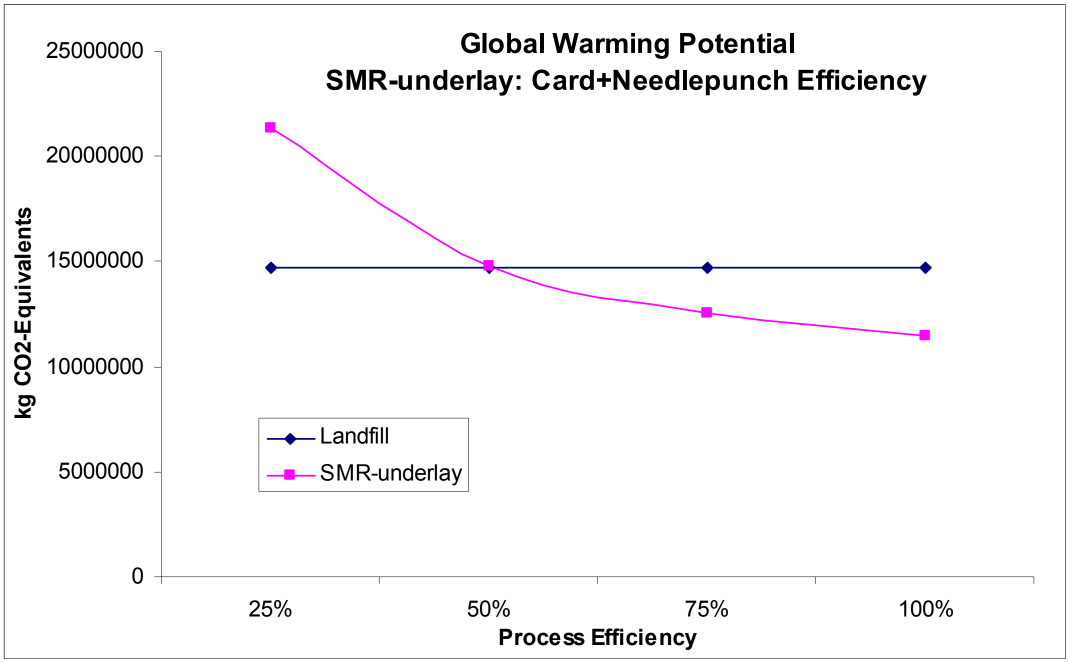

Figure 9.9: Effect of Card+Needlepunch Efficiency on Global Warming Potential

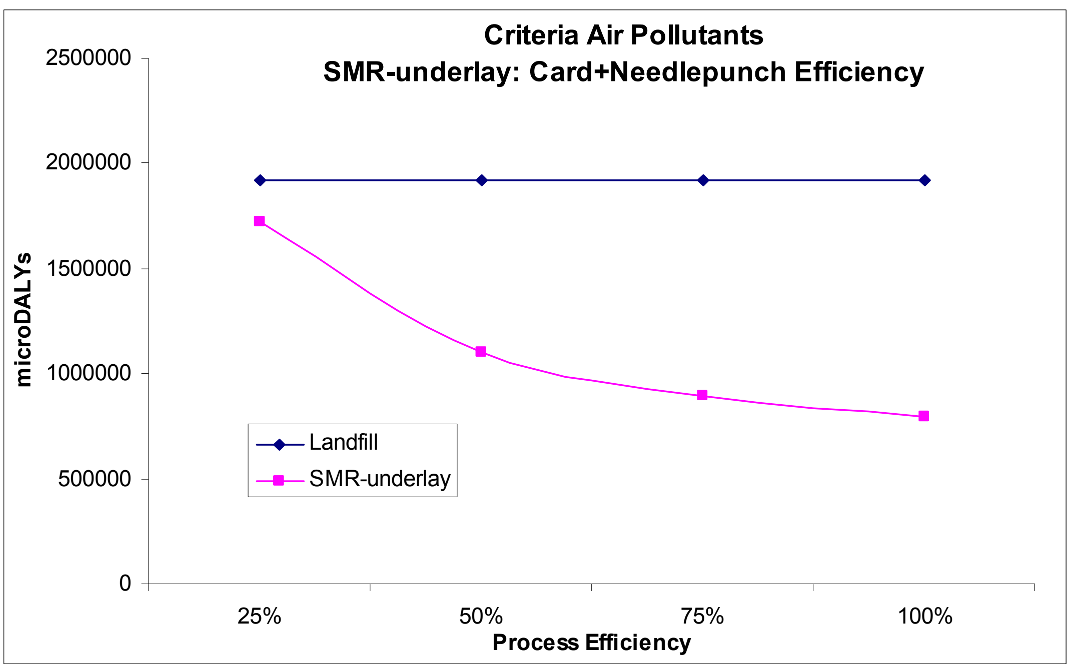

Figure 9.10: Effect of Card+Needlepunch Efficiency on Criteria Air Pollutants

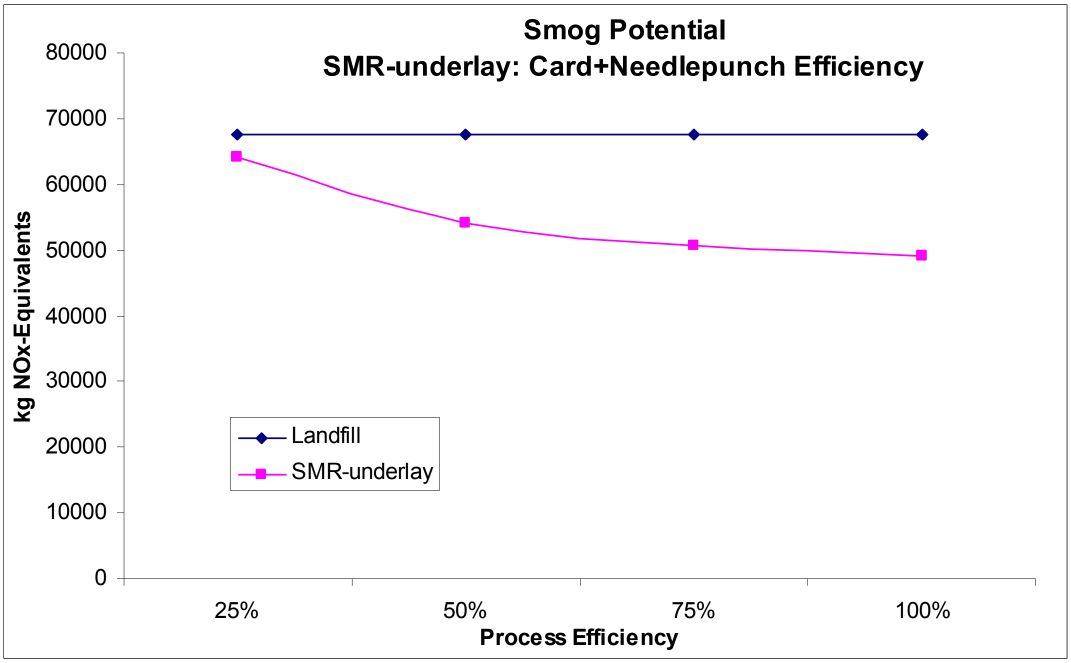

Figure 9.11: Effect of Card+Needlepunch Efficiency on Smog Potential

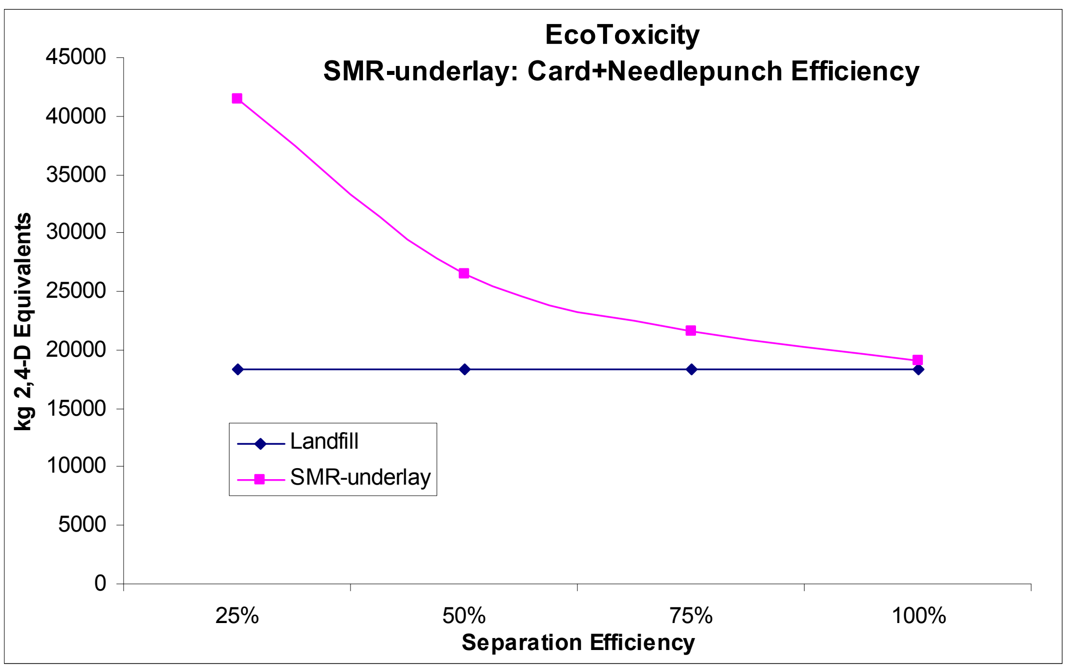

Figure 9.12: Effect of Card+Needlepunch Efficiency on EcoToxicity

9.3.1.4 <u>Secondary Material Reclamation – Nylon 66: Material Separation</u>

The effects of the material separation process on the EOL recommendations are explored for the SMR-N66 scenario. The following four graphs, found in Figure 9.13

through Figure 9.16, demonstrate the impact of the material separation process efficiency on the environmental recommendation for the waste management of PCC-broadloom N66 materials. In this case, it appears that the separation process efficiency has no effect on the EOL recommendation based on environmental criteria. The SMR-N66 option is preferred in the GWP, CAPs, and Smog Potential categories while WD is proffered for its lower EcoToxicity impacts. These recommendations do not change with changes to process efficiencies.

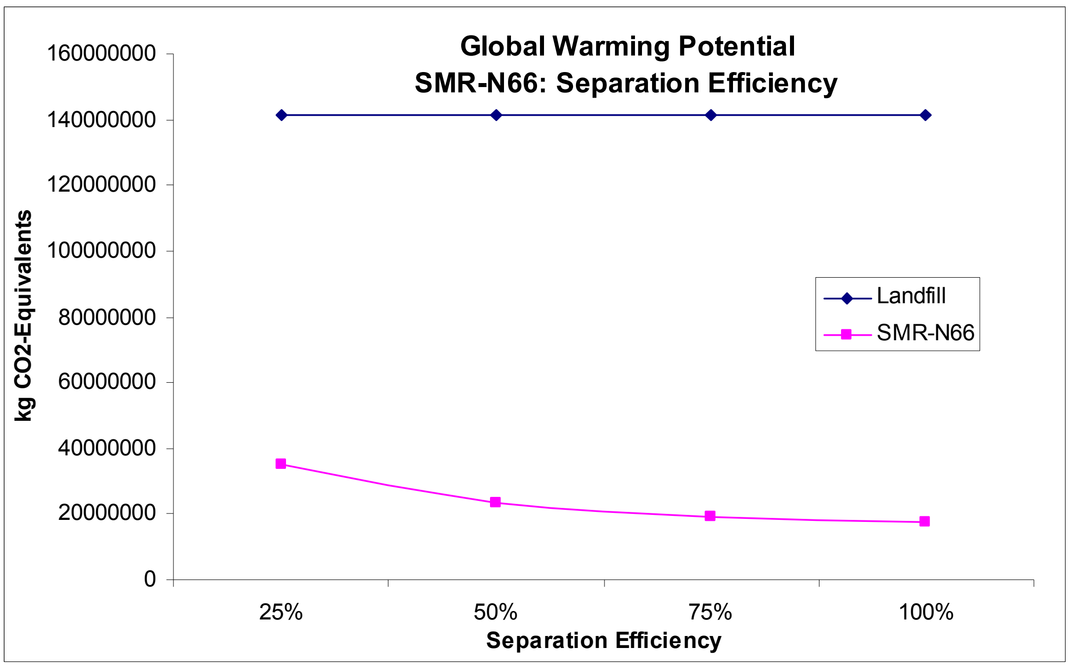

Figure 9.13: Effect of Separation Efficiency on Global Warming Potential

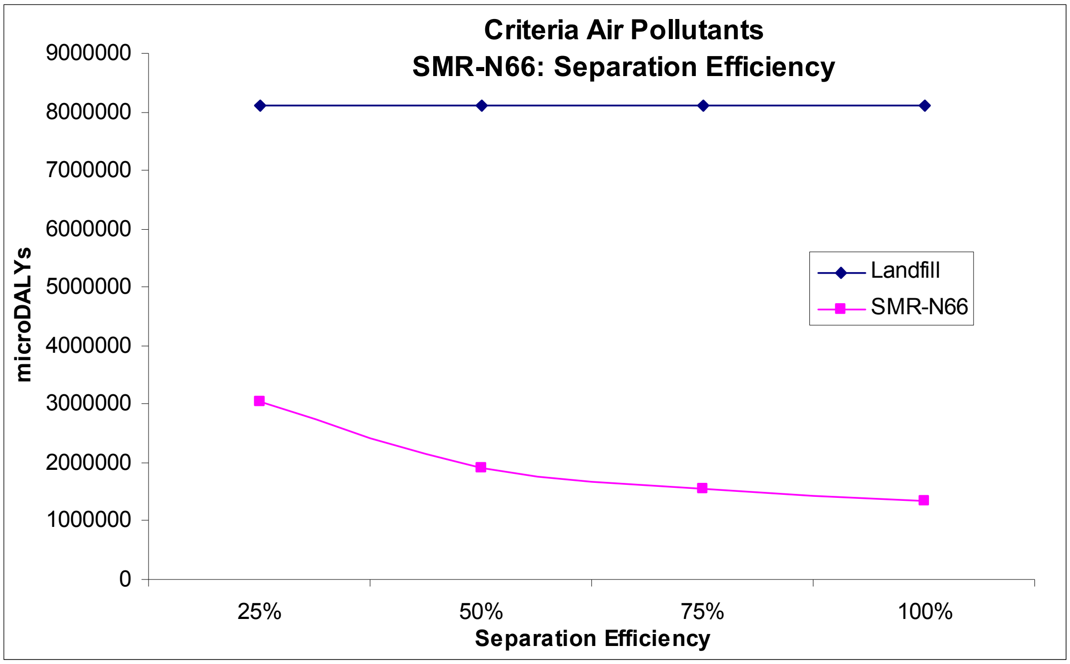

Figure 9.14: Effect of Separation Efficiency on Criteria Air Pollutants

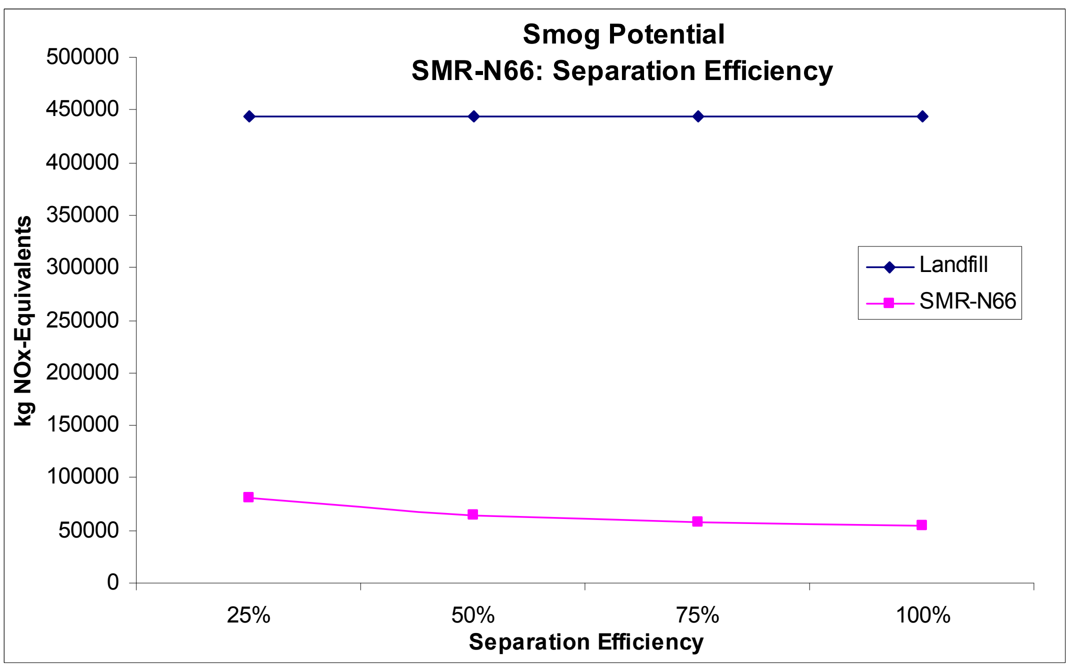

Figure 9.15: Effect of Separation Efficiency on Smog Potential

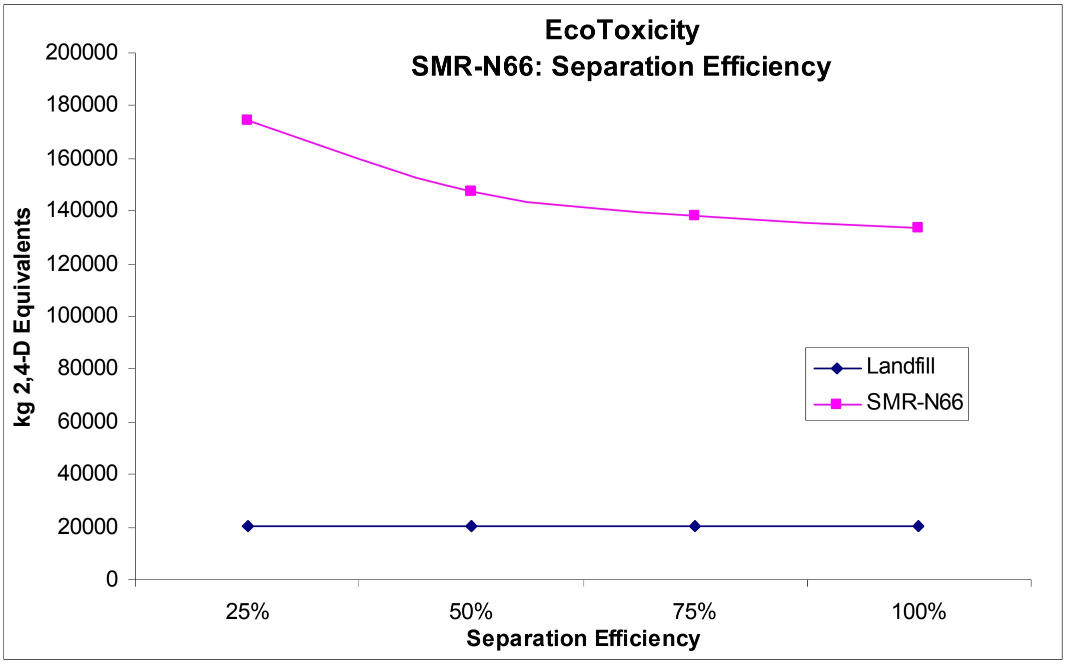

Figure 9.16: Effect of Separation Efficiency on EcoToxicity

9.3.2 Local Versus National Data

The claim in this study is to assess the localized impacts of various waste management options for PCC in urban regions. Thus, localized data was used when available. The most localized data came from energy emissions based on the Georgia grid mix and plant pollution rates and Atlanta metropolitan labor wage rates as reported by the BLS. To following two sections test the sensitivity of the EOL recommendations based on the localized data used for electricity consumption and wage rates.

9.3.2.5 <u>Labor Wages</u>

The following table breaks down the hourly wage rates for all of the employment categories used in this study by localized Atlanta metropolitan data and nationally aggregated data.

Table 9.11: Localized and National Wage Rates

Process	SEC code:	Local [$/hr]	National [$/hr]
collection	53-3032	$16.60	$18.06
transportation	53-3032	$16.60	$18.06
bale	53-7063	$11.80	$12.15
shred	51-6062	$13.21	$11.31
grind	51-6062	$13.21	$11.31
separation	51-9012	$14.98	$17.91
pelletize	51-6064	$13.78	$11.44
card+punch	51-6063	$13.08	$12.00
depoly.	51-9011	$19.75	$21.28
dryer	51-9011	$19.75	$21.28
cleaning	37-2011	$10.14	$10.92

Generally, the national rates are slightly higher than the localized labor rates. For each of the EOL scenarios explored in this study, the effects that the difference in wage rates have on labor costs and total costs are explored. The results are summarized in Table 9.12 and

Table 9.13. The difference in hourly rates translates to increases of total labor costs ranging from about 2% to 10%. This correlates to total costs increases of 0.5% to 4%. Although the localized and national rates do lead to some final impact variations, the differences would not necessarily alter the final recommendations based on economic or social impact. However, the localized data does more accurately reflect the annual labor compensations to be expected by the alternate EOL scenarios. This annual differences are on average a few hundred thousand dollars different for all scenarios.

Table 9.12: Effects of Localized versus National Wage Rate Data on Total Labor Costs

Scenario	Local Data	National Data	% Difference
RMR	$1,752,979	$1,904,180	8.63%
PMR-PVC	$268,444	$277,267	3.29%
PMR-N6	$2,555,655	$2,651,874	3.76%
SMR-underlay	$2,961,355	$3,015,959	1.84%
SMR-N66	$2,495,757	$2,585,378	3.59%

Table 9.13: Effects of Localized versus National Wage Rate Data on Total Costs

Scenario	Local Data	National Data	% Difference
RMR	$3,956,330	$4,107,531	3.82%
PMR-PVC	$542,844	$551,667	1.63%
PMR-N6	$8,372,018.49	$8,468,238.42	1.15%
SMR-underlay	$6,348,571	$6,403,175	0.86%
SMR-N66	$23,178,640	$23,268,261	0.39%

9.3.2.6 Energy Mix

The other category of truly localized data used in this study is the pollution rates associated with the electricity consumption. The mixes are a little different for the Georgia and national grids. The national mix is approximately 50% coal, 20% natural gas, and 20% nuclear. The Georgia mix is broken down by 65% coal and 26% nuclear. The difference in pollution rates are summarized below. In addition to the variation in pollution rates, the market price of electricity for industrial use is different. The localized rate is 5.59¢/kWh while the national cost is more around 3.36¢/kWh.

Table 9.14: National and Local Electricity Pollution Emission Rates

Grid	NO_x [g/kWh]	SO_2 [g/kWh]	CO_2 [g/kWh]	Hg [g/kWh]
Georgia	0.77	4.13	629.74	0.000012
National	0.96	2.47	618.80	0.000012

On average, the national emission rates are lower than that of Georgia for electricity production. This is due to the decreased dependence on coal nationally. The impact of these differences on the total cost and aggregated environmental categories for each of the EOL scenarios are summarized in the following tables.

Table 9.15: Impact of Local versus National Data on Total Energy Costs

Scenario	Local Data	National Data	% Difference
RMR	$267,956	$305,585	14.04%
PMR-PVC	$90,781	$103,529	14.04%
PMR-N6	$807,487	$920,882	14.04%
SMR-underlay	$1,074,075	$1,224,906	14.04%
SMR-N66	$793,300	$904,703	14.04%

Table 9.16: Impact of Local versus National Data on Total Costs

Scenario	Local Data	National Data	% Difference
RMR	$3,956,330	$3,993,959	0.95%
PMR-PVC	$543,914	$556,662	2.34%
PMR-N6	$8,385,935.06	$8,499,329.88	1.35%
SMR-underlay	$6,199,060	$6,349,892	2.43%
SMR-N66	$23,215,626	$23,327,029	0.48%

Table 9.17: Impact of Local versus National Data on GWP [g-CO_2 equivalents]

Scenario	Local Data	National Data	% Difference
RMR	3018651123	2966219951	-1.74%
PMR-PVC	1022689068	1004925907	-1.74%
PMR-N6	9096720812	8938719204	-1.74%
SMR-underlay	12099961162	11889796053	-1.74%
SMR-N66	8936903539	8781677809	-1.74%

Table 9.18: Impact of Local versus National Data on CAPs [microDALYs]

Scenario	Local Data	National Data	% Difference
RMR	284541	174780	-38.57%
PMR-PVC	96400	59214	-38.57%
PMR-N6	857467	526701	-38.57%
SMR-underlay	1140556	700589	-38.57%
SMR-N66	842403	517447	-38.57%

Table 9.19: Impact of Local versus National Data on Smog Potential [g-NO_x equivalents]

Scenario	Local Data	National Data	% Difference
RMR	4576822	5676448	24.03%
PMR-PVC	1550582	1923124	24.03%
PMR-N6	13792278	17106007	24.03%
SMR-underlay	18345735	22753476	24.03%
SMR-N66	13549966	16805477	24.03%

Table 9.20: Impact of Local versus National Data on ExoToxicity [g-2,4-Dequivalents]

Scenario	Local Data	National Data	% Difference
RMR	6831181	6831181	0.00%
PMR-PVC	2314336	2314336	0.00%
PMR-N6	20585798	20585798	0.00%
SMR-underlay	27382104	27382104	0.00%
SMR-N66	20224133	20224133	0.00%

Based on the summarized results in the preceding tables, the economic difference of 14% for total energy costs and 0.5%-3% increases in total costs would not have much effect on the recommended outcome based on overall economic impact of the EOL alternatives being comparatively assessed. However, the difference in environmental impacts can be much more influential on the environmental bottom line. Where data differences exist between the local and national emission rates, the ultimate impact could be of concern. The difference in the two data sets appears to have the most influence over the CAPs and Smog Potential categories. Based on this data, the EOL recommendations could be effected by difference in these two datasets. This would only be amplified by greater variations in energy grid mixes depending on the particular energy climate of a given which could be effected by factors such as alternative energy availability or local legislation.

9.4 Comparative Assessment Summary of all End-of-Life Scenarios

This section will assess the EOL waste management strategies comparatively against each other highlighting the costs, environmental, social, and economic, on a per-kg-recyclable material basis. Thus, each per kg unit is dependent on the scenario, but represents the impacts associated with the recapturing and processing of 1kg of post-consumer recycled material, which presumable has some monetary value or second-life purpose. In as sense, these numbers would create a LCI dataset for the recycled-content materials that could be used as part of a second-life LCA. This uniform comparison is designed to highlight the scenarios with the greatest impacts or highest possibilities of success or failure. This assessment will help to direct the attention required by further study to focus on the scenarios that appear to be the most promising for future development and actual implementation.

9.4.1 Environmental Impact Comparisons

Here, each of the aggregated environmental impact categories will be discussed individually for the comparative assessments based on the baseline assumptions and scenarios. These comparative assessments highlight the potential improvements (although in some cases these "improvements" might turn out negative indicating a worsening of conditions) between the landfill scenario and the particular EOL scenario studied. In other words, the differences are calculated by the environmental impact of the landfill scenario per kg-recyclable material minus the environmental impact of the alternative EOL scenario per kg-recyclable material.

Global Warming Potential

In the assessment of changes in GWP for the various EOL comparisons found in Figure 9.17, it appears that improvements are possible in only four of the five scenarios. These scenarios are the RMR, PMR-PVC, PMR-N6, and SMR-N66. The SMR-underlay scenario appears to show some increased GWP per kg-recyclable material, although the difference is so small, the results as is are somewhat inconclusive. Focusing on four scenarios that demonstrate the most GWP improvement, the RMR and SMR-N66 scenarios appear to offer savings of nearly 6kg CO_2 equivalents per kg-recyclable material. Based on the PIEs for Nylon broadloom, N66, and N6face fibers this would lead to annual CO_2 equivalent reductions of approximately 240million, 66million, and 37million kilograms respectively. The PMR-PVC scenario, averaging about 2kg CO_2 equivalent improvements per kg-recyclable material, has the potential of reducing the CO_2 equivalent emissions by 7million kilograms per year.

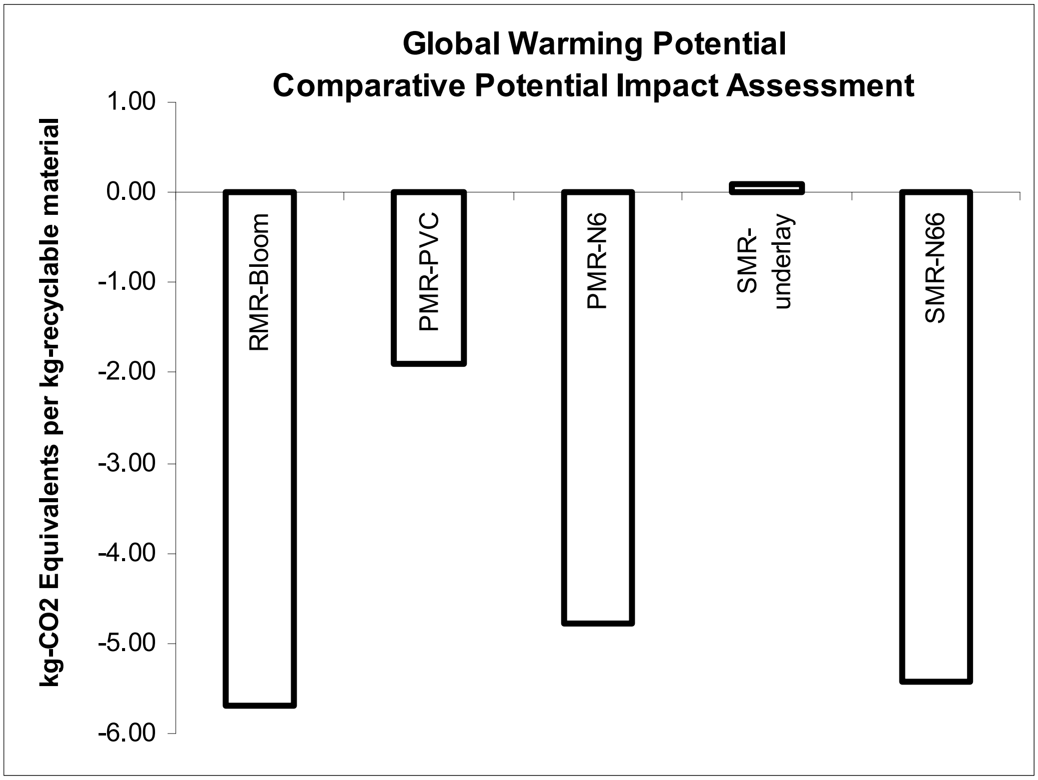

Figure 9.17: Comparative Global Warming Potential Impact Assessment

Human Health: Criteria Air Pollutants

In the assessment of changes in CAPs for the various EOL comparisons found in Figure 9.18, it appears that improvements, albeit small, are possible all five scenarios. Out of all of the scenarios, the RMR scenario demonstrates the possibility for the greatest positive impact, with the potential to eliminate approximately 26million g-microDALYs per year. The PMR-PVC, SMR-N6,6 and PMR-N6 scenarios could potentially lead to a reduction of 888,000, 16.5million, and 735,000 g-microDALYs respectively per year. Even the scenario with the least improvements pre kg-recyclable material shows an annual improvement of around 920,000 g-microDALYs.

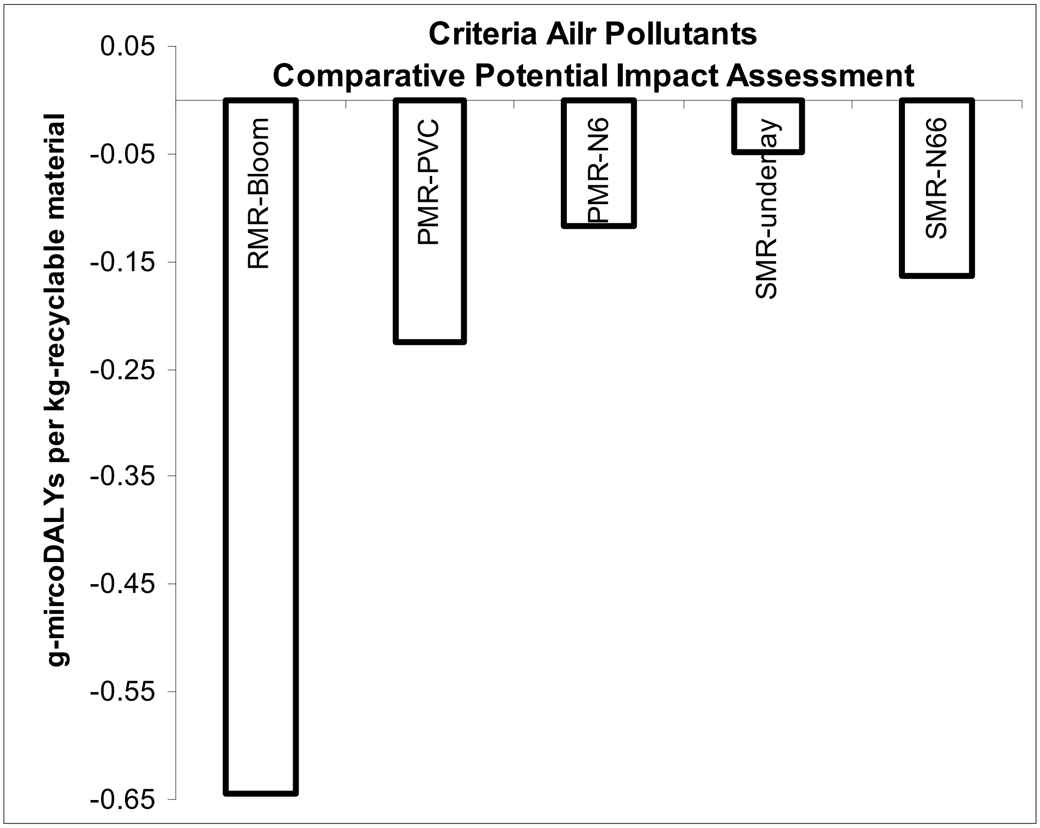

Figure 9.18: Comparative Human Health: Criteria Air Pollutants Impact Assessment

Smog Potential

The third environmental impact category considered is Smog Potential. Based on the results presented in Figure 9.19, there appears to be potential improvements in all EOL scenarios compared to their respective landfill counterparts. The SMR-underlay scenario, although it does demonstrate the potential for some improvements, the per kg-recyclable materials savings are small and thus relatively inconclusive. Conversely, the RMR, SMR-N66, PMR-N6, and PMR-PVC scenarios have the potential to save 1billion, 165million, 96million, and 36million g-NO_x equivalents annually.

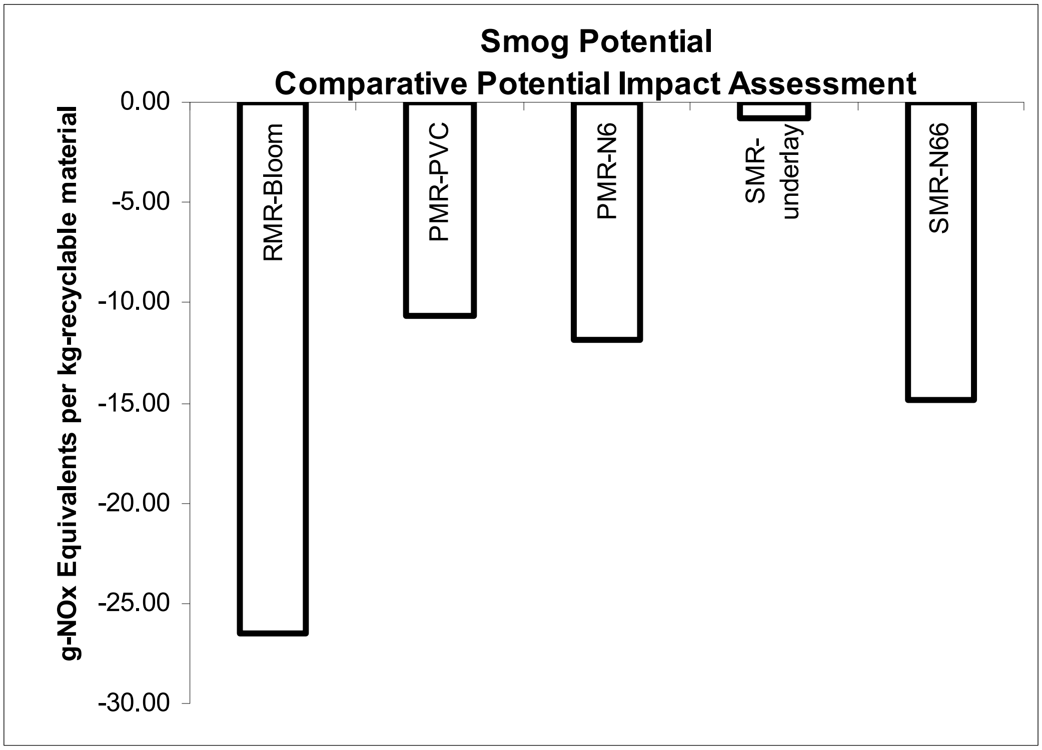

Figure 9.19: Comparative Smog Potential Impact Assessment

EcoToxicity

According to Figure 9.20, it appears that the most difficult environmental impact to overcome in this comparative LCA is the EcoToxicity category. In three out of the five comparisons, the alternative waste management solution demonstrates increased environmental impacts. The RMR and PMR-PVC scenarios are the only scenarios that show improvements over the landfill and replacement baseline EOL scenario. The other scenarios all appear to show increase in EcoToxic pollution; however, the reasons for the increases are varied. The SMR-N66 scenario's EcoToxicity impact is dominated by the glass fiber additives. The other two scenarios, PMR-N6 and SMR-underlay, only show slight increases in pollution rates over their landfill counterparts. The PMR-N6 scenario is EcoToxicity is dominated by the chemical depolymerization process which is highly energy intensive and requires the addition of an environmentally unfriendly catalyst. The

SMR-underlay scenario is mostly impacted by the energy consumed during the material separation process. It appears, then, that the EcoToxicity impact category is influenced primarily by electricity consumption and virgin material additives. From the results in Figure 9.20, the two scenarios that have the smallest comparative pollution rates to overcome are the PMR-N6 and SMR-underlay scenarios.

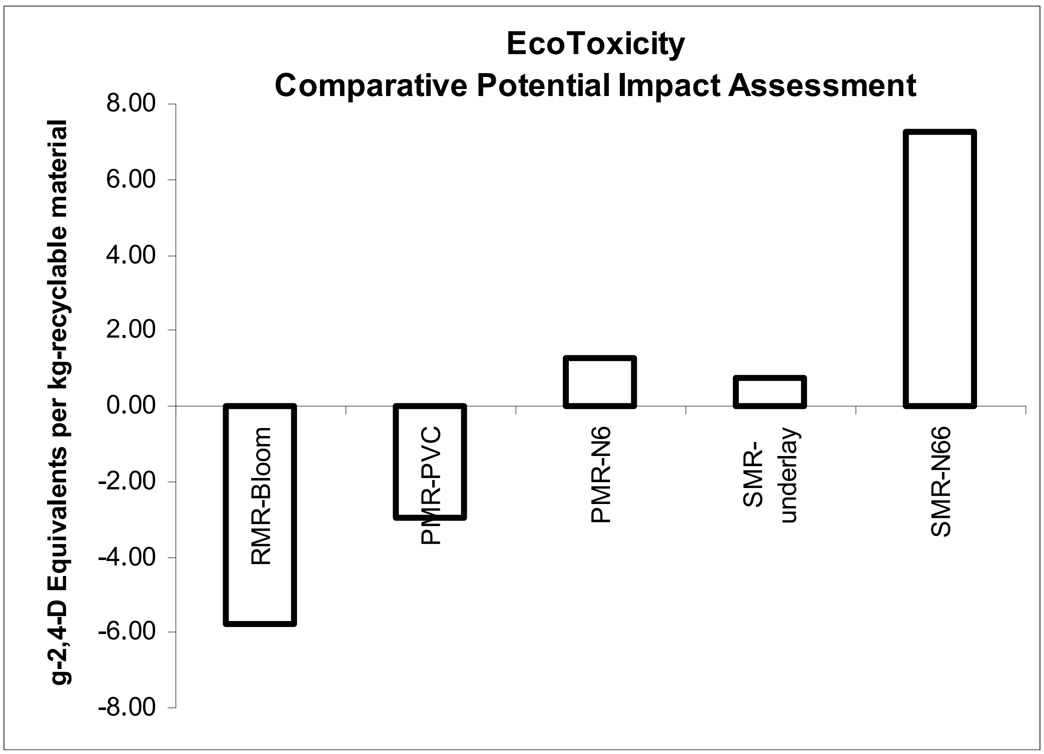

Figure 9.20: Comparative EcoToxicity Impact Assessment

9.4.2 Social Impact Comparisons

Potential Labor Hours

The first social impact category considered is the employment potential quantified by labor hours needed per kg-recyclable material. Because of the LCA scope and boundaries of this assessment, all of the alternative EOL scenario show increases in potential employment. The greatest potential per kg-recyclable material is the PMR-N6 scenario; however, the greatest potential annual increase is realized in the SMR-underlay scenario. These results are reflected in both Figure 9.21 and

Table 9.21. The remaining scenarios, RMR, PMR-N6, SMR-underlay, and SMR-N66, would potentially create upwards of 1,100,000 hours annually. That translates to approximately 375 8-hr shifts a day 365 days a year.

Based on the summarized social impact results discussed above, there are several approaches one could take to capitalize on the increased labor potential resulting from alterations to current PCC waste management practices and carpet design in general. In order to exploit the per kg-recyclable material benefits of the PMR-N6 scenario, the carpet design could be altered to increase the percentage of reclaimable N6 per kg carpet. The PMR-N6 and SMR-N66 scenarios offer the next greatest employment potential; therefore, dedication to their collection could lead to significant employment potential. The same would also apply to the PMR-PVC and RMR scenario.

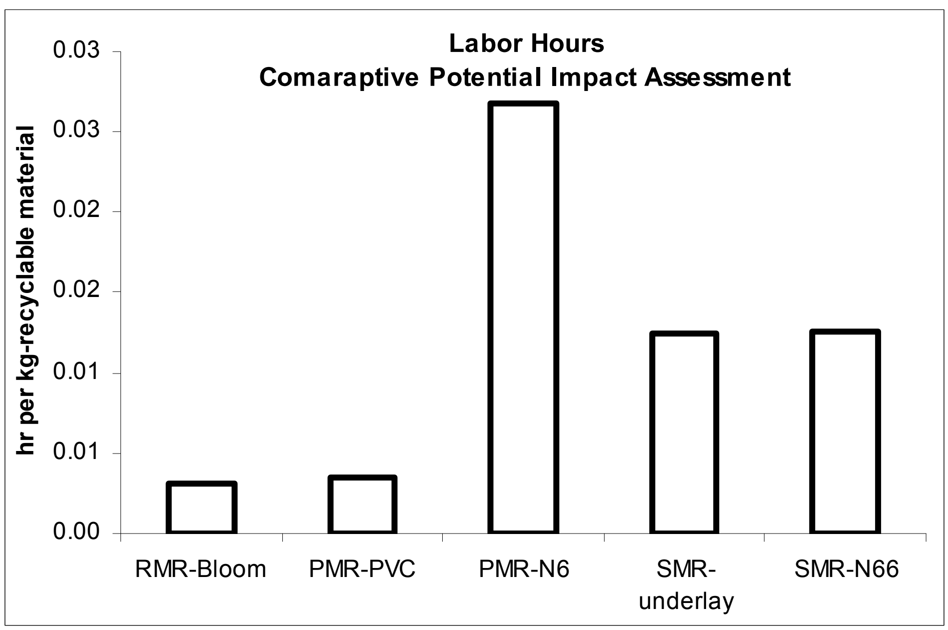

Figure 9.21: Comparative Potential Labor Time Impact Assessment

Table 9.21: Potential Increase in Annual Labor Hours

EOL Option	Potential Increase in Annual Labor [hours]
RMR-Bloom	200,000
PMR-PVC	13,000
PMR-N6	221,000
SMR-underlay	551,000
SMR-N66	221,000

Potential Labor Wages

The second social impact considered is the potential increase in labor wages. The same trends as the potential labor hours just discussed apply to this impact category as well. The annual monetary labor equivalents are summarized in

Table 9.22 while the per kg-recyclable material wage payouts are graphed in Figure 9.22. Based on the per kg-recyclable material rates, recyclers should first focus on the PMR-N6 scenario and then on the two SMR scenarios in order to realized the greatest increase in labor pay.

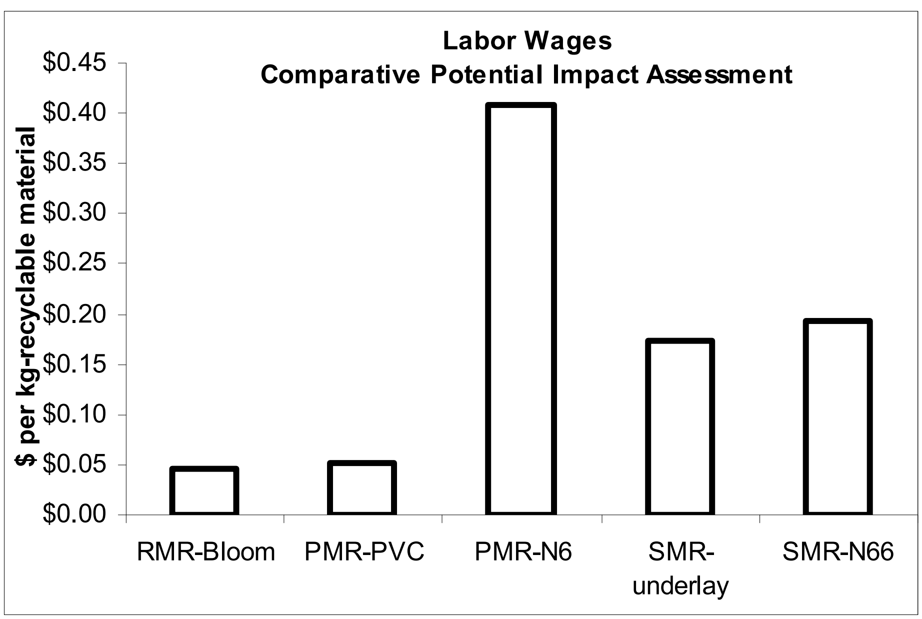

Figure 9.22: Comparative Potential Labor Wages Impact Assessment

Table 9.22: Potential Increase in Annual Labor Wages

EOL Option	Potential Increase in Annual Labor Wages
RMR-Bloom	$2,000,000
PMR-PVC	$185,000
PMR-N6	$2,940,000
SMR-underlay	$3,680,000
SMR-N66	$2,210,000

9.4.3 Economic Impact Comparisons

The last major impact to consider is the economic impacts associated the various EOL comparisons. This category generally is the driving force behind decisions regarding alternations to business and waste management practices. The total economic differences associated with the various comparative assessments on a per kg-recyclable material basis are located in Figure 9.23. According to the rates in the chart, all of the scenarios indicate economic savings potential; in other words, it costs more to dispose of the materials than it would to operate the alternative EOL scenario. Based on these rates, it would appear that the RMR scenario offers the most savings for the manufacturer. However, the assumptions behind the RMR scenario reveal that these savings would not actually be realized because it assumes that the repurposed carpet is donated for its second life; therefore there is no market to recoup the costs incurred in the cleaning. There could be potential tax breaks associated with this scenario, but this type of economic impact is out of the bounds of this assessment.

Focusing on the EOL scenarios that demonstrate the most potential for economic gains, further study should be dedicated to the development of the SMR-N66 and PMR-PVC scenarios followed by the PMR-N6 and SMR-underlay scenarios respectively. These scenarios have potential economic savings ranging from approximately $0.75 to

$1.50 per kg-recyclable material. Not only do this numbers represent the potential savings, but they also offer insight into the flexibility of the scenario to additional or unexpected expenses or the potential monetary incentives that could be offered to initiate and encourage the collection of PCC. Based on the rates, the SMR-N66and PMR-PVC scenarios have the most flexibility with regards to economic uncertainty and incentive, which means that an additional $1.50 per kg-reclaimable N66 or PVC backing materials could be paid by the recycler to spur their collection in order to reap the environmental and social benefits of the alternative EOL scenario while not incurring any increases in costs. This $1.50 per kg-N66 roughly translates to $13.00 per kg PCC-broadloom (assuming 80% of the PCC-bloom market is nylon, 46% of PCC-broadloom is face fiber, and 40% of the market is N6 which equates to approximately 0.15kg-N6 per kg PCC-broadloom). The $1.50 per kg-PVC backing materials correlates to $1.20 per kg PCC-tile. Similarly, incentives of $2.04 and $6.79 could be offered per kg PCC-broadloom for the SMR-underlay and SMR-N66 scenarios respectively.

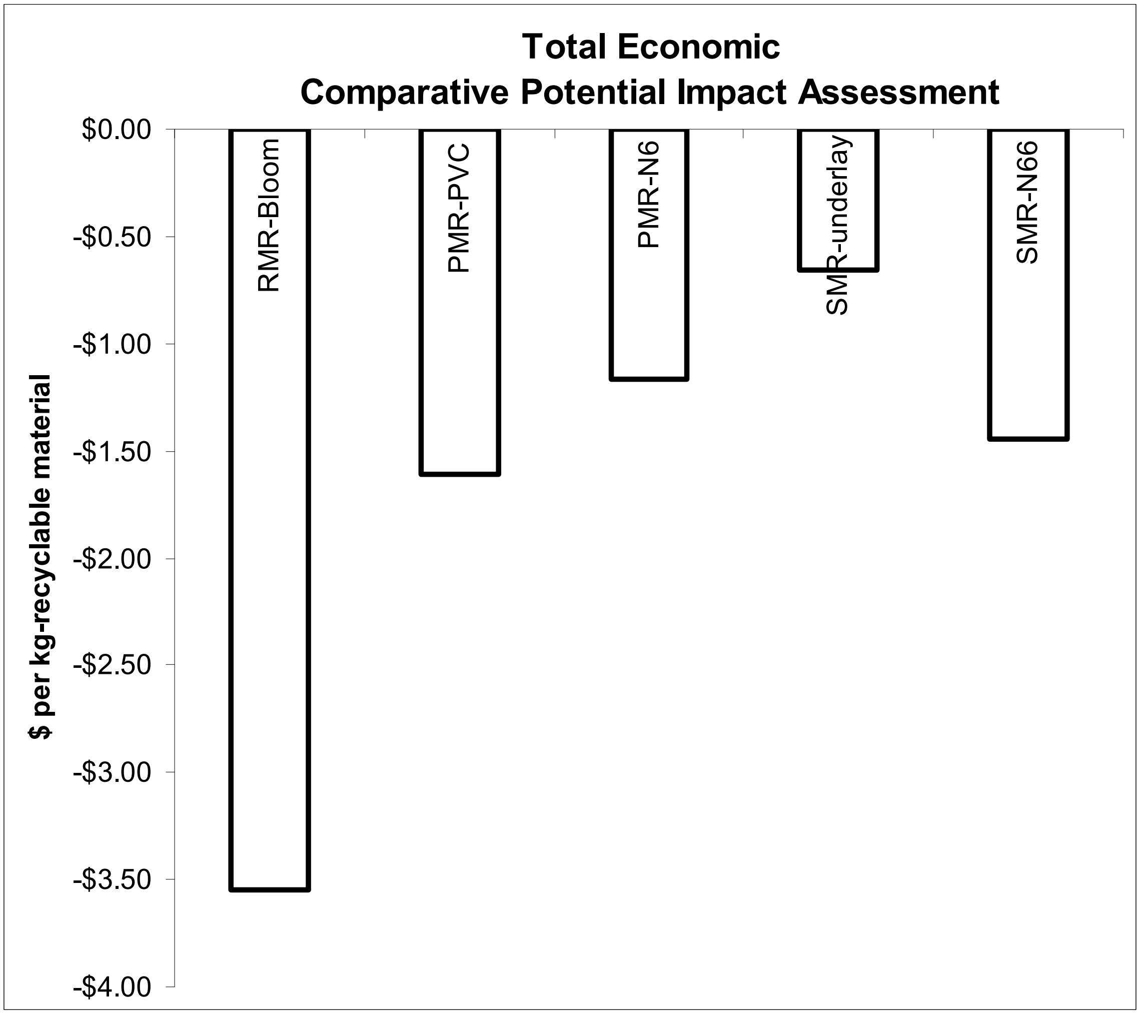

Figure 9.23: Comparative Economic Impact Assessment

Table 9.23: Potential Annual Economic Savings

EOL Option	Potential Annual Economic Savings
PMR-PVC	$5,700,000
PMR-N6	$8,600,000
SMR-underlay	$13,800,000
SMR-N66	$16,500,000

9.4.4 Summary Notes

Although for most of the comparative impact scenarios discussed in this section, the RMR EOL option demonstrates the most potential for improvement on a per-kg recyclable material basis, the total annual improvements are likely over represented. This is due to the fact that the total estimates are a product of the per kg-recyclable material rates and the total available PCC-broadloom. It is impractical to assume that all of the PCC-broadloom disposed of annually is able to be repurposed. Therefore, although the total estimates are greater than the practical reality, it is important to consider the potential impact and improvements that could result from increased repurpose-ability. This scenario clearly has the most potential for environmental savings, thus it would prove beneficial to develop methods and practices that promote the RMR scenario as a waste management options for PCC-broadloom.

The recommendation between the SMR-underlay scenario and its landfill counterpart is rather inconclusive. It is only more attractive in half of the environmental impact categories and its social and economic benefits are not nearly as great pre kg-recyclable material as alternative scenarios. Additionally, the benefits and detriments of the scenario are small and it is likely that they lie within the realm of data uncertainty. Thus, in order to definitively recommend an alternative, process improvements would have to be made to streamline the collection process and increase the efficiency of the unit processes required of the SMR-underlay process.

The three most attractive alternative EOL strategies are the PMR-PVC, SMR-N66 and PMR-N6 scenarios. There are prominent improvements present in all three of these scenarios compared to their respective baseline landfill EOL option in all impact categories except the EcoToxicity environmental impact category. In addition to the impact benefits of these scenarios, they all demonstrate the most total economic flexibility. With the potential cost savings, there exists room within the operational budget of all three scenarios to pay for the PCC, tile and broadloom. This economic flexibility, the abundant availability of the post-consumer nylons for the SMR-N66 and

PMR-N6 scenarios, the 80% yield of recyclable material per kg PCC-tile, the anticipated increase in employment, and the potential to reduce the environmental impacts associated with this post-consumer commodity makes the PMR-PVC, PMR-N6, and SMR-N6 scenarios viable alternatives to landfilling.

CHAPTER 10

CONCLUSIONS AND CLOSURE

10.1 Research Goals Revisited

This section revisits the research questions introduced in Chapter 1. The initial hypotheses are assessed against the findings of this study and are discussed in light of the evolution of this thesis.

10.1.1 Research Question 1

Question 1: What is the environmentally preferred EOL scenario for PCC?

Initial Hypothesis: A closed-loop recycling scenario is the most sustainable and consequently the environmentally preferred EOL option for carpet.

Conclusions: Based on the results of the comparative assessment, it appears that the RMR scenario is the environmentally preferred EOL option for carpet. This result makes sense because there is no remanufacturing of the carpet, only minimal electricity and chemical consumption is required to revamp the PCC-broadloom for its second life. However, although it is the environmentally preferred scenario, it is not necessarily the most practical due to the low repurpose-able carpet yields. Therefore, considering the availability of PCC materials, the PMR-PVC EOL scenario is the most attractive environmentally. In this comparative assessment, it is the environmental costs of the virgin PVC materials that drive the decision in favor of the PMR alternative.

10.1.2 Research Question 2

Question 2: What is the preferred EOL scenario for PCC based on a TBL assessment of the various EOL options? What are the compromises and trade-offs that must be made between environmental, social and economic impact categories?

Initial Hypothesis: The three impact categories are intertwined, thus compromises must be made based on preferences and underlying assumptions made by the assessor. But again, the “closed-loop” recycling strategy would offer the most positive social, economic and environmental impacts.

Conclusions: Although there are inherent trade-offs in a TBL assessment, EOL scenarios do exist in which benefits can be realized in all three major impact categories. In this study, it shows that the PMR-PVC, PMR-N6, and SMR-N66 EOL scenarios see comparative benefits across the board when compared to their equivalent landfill alternatives. In light of these results, yes - EOL preferences do exist along a TBL assessment, even with inherent trade-offs; however, the “closed-loop” recycling hypothesis is not accurate. The type of EOL recycling network does not seem to matter as much as the virgin materials being avoided or the available yield of the recyclable material per material collected.

10.1.3 Research Question 3

Question 3: What are the major hurdles of each EOL scenario for PCC?

Initial Hypothesis: When considering the differences between mining waste in urban regions and mining virgin materials for industrial use, the most prominent difference is the dispersion of materials. The mining of virgin materials for one product occurs in a handful of locations and the materials are shipped to one manufacturing facility. When mining waste in urban regions, bits and pieces of the materials needed are collected from individual households or businesses and then individually transported, or transported in small quantities, to the manufacturing facility. Thus, the actual collection and transportation of goods will be the largest burden to overcome when developing more sustainable urban recycling systems.

Conclusions: The major inhibitors in the various EOL scenarios differ in the economic and environmental impact categories. For the most part, cost of fuel is the major economic hurdle, which correlates to the hypothesis initially stated. However, for the scenarios in which virgin materials are needed in order to complete the EOL process, the acquisition of those materials becomes the inhibitor of the EOL scenario. The environmental inhibitors are mainly the material separation process due to its huge electricity requirements for operation. However, the collection scheme does play a larger role in the RMR scenario. Additionally, the major inhibitor of the SMR-N66 scenario is associated with the virgin glass fibers needed to reinforce the recycled-content plastic pellets. Although the initial hypothesis focused on the burdens of collection, those inhibitors are realized primarily in the economic categories. The environmental inhibitors seem to revolve around processes that require the most electricity for completion. In three instances this occurs in the material separation phase. However, the RMR and SMR-N66 scenarios face environmental resistance due to the burdens associated with the cleaning materials and virgin glass fibers.

Table 10.1: End-of-Life Scenario Economic and Environmental Inhibitors

	Economic Inhibitors	Environmental Inhibitors
RMR	Energy, primarily fuel	Collection: GWP, Smog Potential Cleaning: CAPs, EcoToxicity
PMR-PVC	Energy, primarily fuel	Material Separation Phase
PMR-N6	Chemical Catalyst	Material Separation Phase
SMR-underlay	Energy, primarily fuel	Material Separation Phase
SMR-N66	Virgin Glass Fibers	Virgin Glass Fibers

10.1.4 Research Question 4

Question 4: Is the modified LCA used here offer a standardize method or procedure to comparatively assess the social, economic and environmental impacts of EOL scenarios?

Initial Hypothesis: The modified LCA used here provides users with a method to quantitatively compare social, economic and environmental impacts in a way that isolates the impacts yet still highlights the interconnections between them. The modified LCA used here is by no means a completely comprehensive framework for assessment (in that it does not consider every single potential pollutant or fixed and capital costs associated with individual process or labor requirements of upper-management or auxiliary workers), but it does provide a baseline for studying EOL scenarios from a TBL perspective.

Conclusions: The LCA used in this study has offered a framework in which a meaningful comparative assessment can be conducted. It is still incomplete in that not every pollutant is considered and all costs are not accounted for. However, the major factors in the various impact categories are thoroughly assessed and thus it provides general numbers, figures and results in social, economic and environmental categories to support comparative recommendations. The framework allows for some aggregation of impacts on a functional unit basis so that comparisons can be made across the EOL systems and against other EOL scenarios while at the same time remaining transparent enough to trace back results to the raw data so that further or revamped manipulations of the datasets would be possible if needed to offer new insight to the assessor or client. Therefore, yes, the modified LCA does adequately address the TBL assessment goals of this study as defined by the particular goal and scope section of this LCA.

10.2 Results for a Broader Impact

This study is part of a larger project titled *Material Flow Modeling for Sustainable Industrial Systems for Urban Regions*. The overarching goal of this NSF funded project is to establish a method for assessing the impacts of new manufacturing activities spawned from waste diversion and alternative EOL options for consumer waste on distressed urban areas in such categories as economic development, environmental sustainability, and social implications. The case studies chosen to test these models include PCC and e-waste, particularly CRTs and LCDs. This particular study fits into this grander scheme as a case study for the PCC product, modeling various EOL scenarios and comparatively assessing them according to their respective TBLs based on material and energy flows. It is, however, only a portion of the larger NSF project.

This modified comparative LCA offers several direct and indirect advantages to the overall project. First, a comprehensive LCI was created for the material and process components associated with various carpet EOL alternatives, which has thus created the space within which additional assessments and models can be manipulated within the PCC case study. In addition to the specific PCC related datasets, localized datasets regarding energy grids and transportation matrices were created and can be used to further assess emerging industrial practices in the Atlanta Metropolitan Region. The format for this localized dataset can also be leveraged as a guideline for creating LCI datasets specific to other urban areas of interest. This study also provide economic indicators based on operational expenses which can be scaled up or down to represent annual economic flows that can then be inserted into an Input-Output model and which will then offer insight into the economic implications of the an emerging recycling industry on the overall economic landscape of a particular region. Lastly, with regards to the social impact goals of the larger project, this study offers one method for assessing the employment potential based on throughputs and PIEs of a string of various EOL activities. Lastly, this particular project not only offers the aggregated data and preferred EOL scenario recommendations based on their respective social, economic and environmental impacts as they compare to an equally bound landfill scenario, but also the methods of aggregation and interpretation are transparent so that the method can be duplicated or the individual materials and unit processes can be manipulated to represent new or different variations of the PCC EOL scenarios.

10.3 Future Work

Although this study has led to a series of recommendations based on the comparative assessments of the various EOL scenarios, there is still more work that can be done to further refine the results and to unveil new and perhaps meaningful insight into the realm of alternative waste management and its effects on a TBL. First, a more refined approach to the sensitivity analysis on those EOL scenarios that show the greatest improvement potential in several impact categories could prove beneficial by revealing in more accurate details the tipping points of the individual EOL activities and their respective effects on the overall recommendations. By refining the sensitivity analysis, the areas where improvements in efficiency, management and design are needed would be better understood and thus more developmental attention could be given to those particular areas so that improvements in the overall scenario could be realized.

The uncertainty in data is always an issue when discussing LCAs; therefore, further refinement, specifically of some of the materials whose datasets were aggregated from a variety of databases with sometime vary little correlation, might instill a greater confidence in the overall recommendations of the LCA. Additionally, much of the LCI is not specific to the localized region of the Atlanta urban area. Datasets such as electricity, collection schemes, and employee wages are regionalized due to the localized records of the EIA and BLS and directional agents such as Google Maps, but other material datasets and practices are not localized because the information comes from national, and sometimes foreign, datasets. Therefore, these particular datasets could vary tremendously from region to region if the localized data and impacts were known.

Other than the typical nuances and improvements desired by many LCAs concerning data uncertainty, the overwhelming number of variables and gross assumptions made, the linearity of the framework itself, this particular study is destined for future work in the context of the greater goals of the NSF that funded it. The material and energy flows established in this comparative LCA need to be translated (although some correlations exist in this study as well) into the annual dollars format required for use in an Input-Output model which will assess the direct and indirect economic impacts of the emerging waste management industries on the overall economic situation of a specified region. In conclusion, this study directly contributes a model and means for assessing the environmental impacts of various EOL practices; the same flows established here to assess the pollution costs and/or savings will be adapted to assess the costs and/or savings within an actual economic realm.

10.4 Closure and Lessons Learned

There have been a myriad of lessons learned throughout the development of this research project. First and foremost, it was a lesson into the challenges faced by those looking for a more global or life cycle approach to the environmental impacts associated with consumer products and waste behavior. This field is clearly still in its early development. The standards for assessments are still subject to swings in interpretation and LCI datasets span the entire spectrum of reliability and applicability with regards to any given system or product. Consequently, much thought has been given to determining the most meaningful ways to represent and allocate abstract data such as global warming potential of a particular mechanical process on an estimated amount of material assuming a localized mix of energy on the available grid. However, the challenges of the LCA process are accounted for in the current LCA framework in the interpretation phase. Thus once noted, the assessor must formulate, justify and document assumptions in order to make any forward progress.

The opposite of these almost expected uncertainties in the LCA process were the resulting recommendations of the comparative analysis. Common sense generally advocates for the typical reduce, reuse, and recycle approach to waste management, but rarely does one question the reasoning behind this mantra. Thus, this study has proved insightful in that recycling is not always the “best” alternative in every given instance. Sometimes the environmental costs of the collection scheme, or the mining of the recyclable materials, lumped with the mechanical and chemical activities required of the recycling process is greater than that of simply acquiring the virgin materials again. Additionally, it has been interesting to systematically work through the various EOL scenarios to uncover the major inhibitors and enablers of the various schemes. Attaching numbers – money, pollution rates, labor hours, etc. – to individual process gives new clarity to the direct and indirect implications associated with manufacturing process and various stages of a products life cycle. It highlights system inefficiencies and wasteful processes in general, which leaves the question of the overall efficiencies of the industrial world and the consumer behaviors that have contributed to the propagation of the declining environmental state.

In conclusion, there is no one definitive EOL strategy; instead the recommendations based on modified TBL approaches to LCAs are conditional and based on specific comparisons between given scenarios. However, the challenges inherent in the development of the unique LCIs and LCAs are ultimately outweighed by the benefits from insight gained into the various scenarios. This insight can then lead to improvements in waste management strategies and increased process efficiencies in order to realize the benefits - social, economic and environmental - of sustainable industrial practices.

APPENDIX A
PRODUCT INVENTORY ESTIMATES AND COLLECTION

A.1 Post-Consumer Broadloom Carpet Annual Estimates by Zip Code

	PCC-broadloom			PCC-broadloom			PCC-broadloom			PCC-broadloom	
zipcode	**lower**	**upper**	**zipcode**	**lower**	**upper**	**zipcode**	**lower**	**upper**	**zipcode**	**lower**	**upper**
30090	0	0	**30337**	144756	202658	**30314**	244629	342481	**30236**	380088	532123
30247	0	0	**30122**	145863	204208	**30294**	246519	345127	**30064**	380196	532274
30304	0	0	**30307**	149814	209740	**30329**	250848	351187	**30040**	381996	534794
30334	0	0	**30132**	157734	220828	**30157**	252045	352863	**30080**	391248	547747
30361	0	0	**30354**	161343	225880	**30328**	258309	361633	**30135**	391365	547911
30363	0	0	**30265**	163242	228539	**30338**	259965	363951	**30331**	399996	559994
30369	0	0	**30252**	167418	234385	**30078**	262017	366824	**30034**	404253	565954
30336	2142	2999	**30013**	167931	235103	**30518**	262647	367706	**30075**	416079	582511
30326	9675	13545	**30309**	168651	236111	**30088**	262899	368059	**30127**	424359	594103
30346	13068	18295	**30519**	172026	240836	**30297**	267813	374938	**30067**	433044	606262
30105	22095	30933	**30035**	172359	241303	**30341**	279324	391054	**30281**	441837	618572
30259	22374	31324	**30019**	177327	248258	**30350**	279513	391318	**30093**	447021	625829
30079	23067	32294	**30115**	180684	252958	**30008**	281970	394758	**30066**	458946	642524
30205	24678	34549	**30312**	181989	254785	**30238**	283005	396207	**30096**	472437	661412
30220	28044	39262	**30324**	182853	255994	**30134**	286524	401134	**30318**	479061	670685
30303	33696	47174	**30168**	185076	259106	**30068**	286902	401663	**30047**	481248	673747
30183	34434	48208	**30327**	189027	264638	**30274**	289494	405292	**30022**	490077	686108
30290	46638	65293	**30228**	190656	266918	**30084**	291699	408379	**30349**	497151	696011
30002	47700	66780	**30306**	190791	267107	**30269**	292122	408971	**30083**	502119	702967
30187	54810	76734	**30305**	192420	269388	**30316**	292455	409437	**30058**	525654	735916
30288	58698	82177	**30214**	197532	276545	**30087**	293598	411037	**30032**	539208	754891
30268	63162	88427	**30071**	199980	279972	**30041**	294264	411970	**30062**	555066	777092
30107	72495	101493	**30114**	200907	281270	**30189**	297360	416304	**30043**	560106	784148
30276	81522	114131	**30345**	205119	287167	**30102**	297459	416443	**30044**	598104	837346
30313	99315	139041	**30082**	208719	292207	**30310**	302382	423335	**TOTAL**	**33,293,871**	**46,611,419**
30248	100359	140503	**30260**	209475	293265	**30052**	314703	440584			
30273	102708	143791	**30038**	213237	298532	**30092**	316305	442827			
30308	106164	148630	**30012**	213399	298759	**30311**	317070	443898			
30291	110295	154413	**30021**	219366	307112	**30024**	317169	444037			
30017	111213	155698	**30097**	219393	307150	**30060**	323820	453348			
30039	116154	162616	**30030**	226233	316726	**30188**	329517	461324			
30141	116667	163334	**30342**	232263	325168	**30344**	330777	463088			
30317	125829	176161	**30094**	238608	334051	**30045**	330921	463289			
30360	133038	186253	**30126**	238725	334215	**30319**	331047	463466			
30213	133317	186644	**30215**	238995	334593	**30144**	349866	489812			
30277	139392	195149	**30253**	239373	335122	**30101**	352179	493051			
30106	139419	195187	**30152**	242316	339242	**30315**	362592	507629			
30339	142038	198853	**30340**	242973	340162	**30263**	371583	520216			
30337	144756	202658	**30033**	243414	340780	**30004**	372105	520947			
30122	145863	204208	**30005**	243675	341145	**30076**	377928	529099			

Table 10.2: PIEs for PCC-broadloom by Zip Code [kg PCC-broadloom/year]

A.2 Distance Matrix: Zip Codes to Recycling Facilities

ZIP	Calhoun	Dalton	ZIP	Calhoun	Dalton	ZIP	Calhoun	Dalton
30092	76	93	**30269**	98	116	**30346**	67	85
30093	76	96	**30273**	91	109	**30349**	82	100
30094	94	112	**30274**	86	104	**30350**	71	91
30096	79	97	**30276**	112	130	**30354**	79	96
30097	82	100	**30277**	104	122	**30360**	72	90
30101	44	62	**30281**	94	114	**30361**	69	89
30102	44	61	**30288**	80	98	**30363**	68	86
30105	17	37	**30290**	91	109	**30369**	69	89
30106	61	81	**30291**	85	103	**30518**	96	115
30107	59	68	**30294**	86	104			
30114	47	64	**30297**	82	100			
30115	51	71	**30303**	72	89			
30122	80	98	**30304**	77	97			
30126	69	87	**30305**	65	83			
30127	53	73	**30306**	71	91			
30132	48	66	**30307**	73	91			
30134	61	79	**30308**	71	88			
30135	90	108	**30309**	68	86			
30141	56	74	**30310**	74	92			
30144	47	65	**30311**	73	90			
30152	46	66	**30312**	71	87			
30157	54	74	**30313**	70	87			
30168	75	93	**30314**	73	90			
30183	35	53	**30315**	74	92			
30187	93	111	**30316**	75	95			
30188	55	75	**30317**	76	94			
30189	46	66	**30318**	67	87			
30205	108	126	**30319**	69	87			
30213	87	107	**30324**	70	88			
30214	91	109	**30326**	65	85			
30215	99	117	**30327**	63	80			
30220	115	133	**30328**	64	82			
30228	98	116	**30329**	72	90			
30236	88	108	**30331**	72	92			
30238	90	107	**30334**	71	89			
30247	80	101	**30336**	75	92			
30248	107	124	**30337**	80	98			
30252	108	126	**30338**	70	87			
30253	97	117	**30339**	62	80			
30259	112	130	**30340**	73	90			
30260	87	104	**30341**	72	90			
30263	109	126	**30342**	64	84			
30265	99	117	**30344**	79	97			
30268	96	114	**30345**	74	93			

Table 10.3: Distance Matrix - Zip COdes to Recycling Facilities

A.3 Goodwill Collection Scheme MatLab Code

```
clear all
%Cost & Energy Estimates for GW collection sites
%Placement of Goodwill collection sites
%for collecting carpet in 13-county Atlanta Metropolitan Region
%gw=Goodwill Collection Site
%zp=zip code
%d=distance
```

```
%-----------------------------------------------------------------

%population for each of 142 zip codes for Atlanta Metro Region
pop = xlsread('ZiPpopulation.xls');

%Distances
%distances from each zip code to Goodwill locations
d_zp_to_GW = xlsread('GWmatrix.xls');
%distances from possible collection site to recycle facility
d_GW_to_R = xlsread('distanceGWtoR.xls');


%Capacities
%capacity of collection 6 (short) ton bin [kg]
cap_GW = 4536;
%full capacity of bin [kg]- using HDDV-8A
cap_HDDV=4536;


%annual disposal rate [kg/person/year]- residential carpet only
disposed = 12*0.9;


%energy rates
FE=6.8;    %[miles/gallon]: HDDV-3
E=1/FE;     %[gallons fuel per mile]
MPH = 55;    %average speed

%costs
cost_GW=5425;    %annual cost of bin rental
cost_fuel=3.867;  %[$/gallon]
cost_driver=16.60;  %[$/hour]
cost_d=cost_driver*(1/MPH)+E*cost_fuel; %[$/mile]

%----------------------------------------------------------------------
--

%Estimated yearly carpet disposal for each zip code
%GW open: set variable @ 2
%GW closed: set variable @ 1
carpet = disposed .* pop ;

    for h=2
        goodwill(1)=h-1;
    for j=2
        goodwill(2)=j-1;
    for k=2
        goodwill(3)=k-1;
    for l=2
        goodwill(4)=l-1;
    for m=2
        goodwill(5)=m-1;
    for n=2
```

```
    goodwill(6)=n-1;
for o=2
    goodwill(7)=o-1;
for p=2
    goodwill(8)=p-1;
for q=2
    goodwill(9)=q-1;
for r=2
    goodwill(10)=r-1;
for s=1
    goodwill(11)=s-1;
for t=2
    goodwill(12)=t-1;
for u=2
    goodwill(13)=u-1;
for v=2
    goodwill(14)=v-1;
for w=2
    goodwill(15)=w-1;
for x=2
    goodwill(16)=x-1;
for y=2
    goodwill(17)=y-1;
for z=2
    goodwill(18)=z-1;
for aa=2
    goodwill(19)=aa-1;
for ab=2
    goodwill(20)=ab-1;
for ac=2
    goodwill(21)=ac-1;
for ad=2
    goodwill(22)=ad-1;
for ae=2
    goodwill(23)=ae-1;
for af=2
    goodwill(24)=af-1;
for ag=2
    goodwill(25)=ag-1;
for ah=1
    collection1(26)=ah-1;
for ai=2
    goodwill(27)=ai-1;
for aj=2
    goodwill(28)=aj-1;
for ak=2
    goodwill(29)=ak-1;
for al=2
    goodwill(30)=al-1;
for am=2
    goodwill(31)=am-1;
for an=2
    goodwill(32)=an-1;
for ao=2
    goodwill(33)=ao-1;
for ap=2
    goodwill(34)=ap-1;
```

```
  for aq=2
      goodwill(35)=aq-1;
  for ar=2
      goodwill(36)=ar-1;
  for as=2
      goodwill(37)=as-1;
  for at=2
      goodwill(38)=at-1;
  for au=2
      goodwill(39)=au-1;
  for av=2
      goodwill(40)=av-1;
  for aw=2
      goodwill(41)=aw-1;
  for ax=2
      goodwill(42)=ax-1;
  for ay=2
      goodwill(43)=ay-1;
  for az=1
      goodwill(44)=az-1;
%sets initial condition of all zip codes at closed for collection
          collection=zeros(1,142);
%sets zip codes w/ goodwills opened/closed depending on trial
          collection(2)=goodwill(1);
          collection(6)=goodwill(2);
          collection(13)=goodwill(3);
          collection(14)=goodwill(4);
          collection(18)=goodwill(5);
          collection(19)=goodwill(6);
          collection(21)=goodwill(7);
          collection(22)=goodwill(8);
          collection(23)=goodwill(9);
          collection(24)=goodwill(10);
          collection(25)=goodwill(11);
          collection(26)=goodwill(12);
          collection(28)=goodwill(13);
          collection(30)=goodwill(14);
          collection(35)=goodwill(15);
          collection(38)=goodwill(16);
          collection(41)=goodwill(17);
          collection(45)=goodwill(18);
          collection(48)=goodwill(19);
          collection(52)=goodwill(20);
          collection(53)=goodwill(21);
          collection(55)=goodwill(22);
          collection(56)=goodwill(23);
          collection(59)=goodwill(24)
          collection(64)=goodwill(25);
          collection(65)=goodwill(26);
          collection(70)=goodwill(27);
          collection(71)=goodwill(28);
          collection(78)=goodwill(29);
          collection(80)=goodwill(30);
          collection(83)=goodwill(31);
          collection(86)=goodwill(32);
          collection(94)=goodwill(33);
          collection(103)=goodwill(34);
```

```
            collection(107)=goodwill(35);
            collection(113)=goodwill(36);
            collection(115)=goodwill(37);
            collection(118)=goodwill(38);
            collection(120)=goodwill(39);
            collection(121)=goodwill(40);
            collection(129)=goodwill(41);
            collection(132)=goodwill(42);
            collection(135)=goodwill(43);
            collection(141)=goodwill(44);


%which collection site is the closest to each zip code?
%this loop adds up all the carpet going to each Goodwill site
           total_carpet_GW = zeros(1,142);
           %inital conditions for  collection
           for i=1:142
               %if all sites closed, no carpet collected, null case
            if collection(i)==0 && sum(collection)==0
                d_zp_to_GW_sum(i)=0;
                index=i;
                %site (i) open, distance between i zip & i goodwill
zero
                    elseif collection(i)==1
                        d_zp_to_GW_sum(i)=0;
                        index=i;
                        %if 1 site open, all carpet to site
                            elseif collection(i)==0 &&
sum(collection)==1
                                step1 = d_zp_to_GW(:,i) .* collection';
                                [d_zp_to_GW_sum(i) index] = max(step1);
                                %if multiple sites open
                                    elseif collection(i)==0 &&
sum(collection)>1
                                        step1 = d_zp_to_GW(:,i) .*
collection';
                                        [d_zp_to_GW_sum(i) index] =
min_no_zeros(step1);
                                        end
                                        total_carpet_GW(index) =
total_carpet_GW(index)+carpet(i);
           end


%How many times is each collection BUCKET picked up?
%considers only truck capacity, not capacity of Goodwill bin
                                        GW_pickup =
ceil(total_carpet_GW / cap_HDDV);


%total distance driven to pick up carpet and return to recycling
facility -
                                        total_d_GW_to_R =
sum(((d_GW_to_R(:,1).*collection').*GW_pickup') * 2);
```

```
%total carpet collected and taken to recycling facility
%compare to total carpet available
                                        xlswrite('CarpetCollected.xls',
total_carpet_GW);
                                        total_carpet_collected =
sum(total_carpet_GW);
                                        total_carpet = sum(carpet);

%total distance driven
                                        total_d = total_d_GW_to_R

%-------------------------------------------------------------------

%Costs
%costs of having a collection site
                                        total_cost_GW = cost_GW *
sum(collection);
%costs from transportation
                                        total_cost_d = cost_d *
total_d;
%total costs
                                        total_cost = total_cost_GW +
total_cost_d


                                        %Energy consumption
                                        e_total=total_d * E

                                    end
                                end
                            end
                        end
                    end
                end
            end
        end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
    end
```

```
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
```

A.4 Goodwill Collection Scheme Distance Matrices

The shaded regions in the matrix below indicated a Goodwill collection site within that particular zip code.

ZIP CODE	Calhoun	Dalton	ZIP CODE	Calhoun	Dalton	ZIP CODE	Calhoun	Dalton	ZIP CODE	Calhoun	Dalton
30002	0	0	30092	74	94	30269	0	0	30346	0	0
30004	64	84	30093	76	96	30273	0	0	30349	0	0
30005	0	0	30094	0	0	30274	0	0	30350	71	91
30008	0	0	30096	78	98	30276	0	0	30354	0	0
30012	0	0	30097	0	0	30277	0	0	30360	0	0
30013	97	117	30101	0	0	30281	94	114	30361	0	0
30017	0	0	30102	0	0	30288	0	0	30363	0	0
30019	0	0	30105	17	37	30290	0	0	30369	0	0
30021	0	0	30106	61	81	30291	0	0	30518	96	115
30022	0	0	30107	0	0	30294	0	0	30519	0	0
30024	0	0	30114	40	60	30297	0	0			
30030	0	0	30115	51	71	30303	0	0			
30032	76	96	30122	0	0	30304	0	0			
30033	90	93	30126	0	0	30305	0	0			
30034	0	0	30127	53	73	30306	71	91			
30035	0	0	30132	0	0	30307	0	0			
30038	0	0	30134	0	0	30308	0	0			
30039	91	111	30135	0	0	30309	0	0			
30040	64	84	30141	0	0	30310	72	92			
30041	0	0	30144	45	65	30311	0	0			
30043	90	110	30152	46	66	30312	0	0			
30044	83	103	30157	54	74	30313	0	0			
30045	92	111	30168	0	0	30314	0	0			
30047	82	103	30183	0	0	30315	0	0			
30052	100	120	30187	0	0	30316	75	95			
30058	90	110	30188	55	75	30317	0	0			
30060	0	0	30189	46	66	30318	67	87			
30062	55	75	30205	0	0	30319	0	0			
30064	0	0	30213	0	0	30324	0	0			
30066	52	71	30214	0	0	30326	65	85			
30067	0	0	30215	0	0	30327	0	0			
30068	0	0	30220	0	0	30328	62	82			
30071	0	0	30228	0	0	30329	70	90			
30075	0	0	30236	88	108	30331	72	92			
30076	73	93	30238	0	0	30334	0	0			
30078	0	0	30247	80	101	30336	0	0			
30079	0	0	30248	0	0	30337	0	0			
30080	60	80	30252	0	0	30338	0	0			
30082	0	0	30253	97	117	30339	0	0			
30083	0	0	30259	0	0	30340	0	0			
30084	75	95	30260	0	0	30341	70	90			
30087	0	0	30263	106	126	30342	64	84			
30088	0	0	30265	0	0	30344	0	0			
30090	0	0	30268	0	0	30345	74	93			

Table 10.4: Distance Matrix - Goodwill to Recycling Facility

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